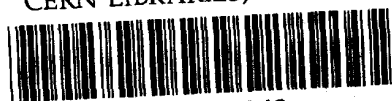




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Cours/Lecture Series

1988-1989 ACADEMIC TRAINING PROGRAMME

LECTURER : R. WIGMANS (CERN/EF)

TITLE : Calorimetry in high-energy physics

DATES : January 25, 26, 27, 1989

TIME : 11h to 12h

PLACE : Auditorium

ABSTRACT

Calorimeters play an increasingly important role in high-energy experiments. In order to be able to optimize the performance of these detectors, it is absolutely necessary to understand in detail how they work. This is the subject of these lectures.

We will review the processes through which particles lose energy in dense matter (shower development), and the factor determining the response of an instrumented block of dense matter.

Emphasis will be put on sampling calorimeters, although homogeneous devices for electromagnetic shower detection will be treated as well. The so-called compensation mechanisms, crucial for the performance of hadron calorimeters, will be discussed in detail.

Finally, some attention will be given to current R & D work carried out in view of the very demanding requirements of experiments at future supercolliders.

Lecture Notes Distribution : - internal (CERN) distribution only to Participants

- self-service (50 copies) at CERN Main Library

- No extra copies available
- Reference copy at Main Library

CALORIMETRY IN HIGH-ENERGY PHYSICS

Richard Wigmans
CERN

Academic Training CERN, Jan. 25-27, 1989

OUTLINE:

- Principles of calorimetry
- Comparison of different techniques
- Limitations
- Research and development

NO emphasis on details of specific detectors.

Lecture 1: Principles, EM Calorimeters

Lecture 2: Techniques, HADRONIC Calorimeters

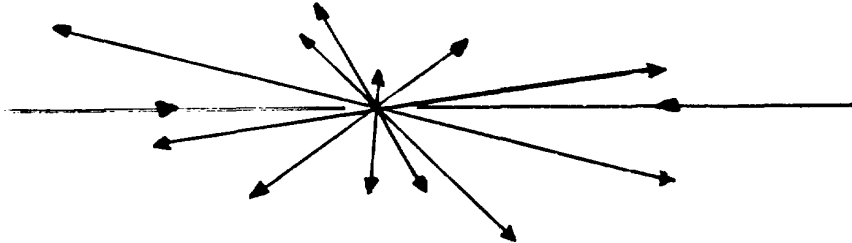
Lecture 3: Compensation, R&D

LITTTERATURE:

- Nucl. Instr. and Meth. **A259** (1987) 389
- Nucl. Instr. and Meth. **A265** (1988) 273
- Proc. ICFA School on Instrumentation in Elementary Particle Physics,
Trieste 1987, p. 41-149

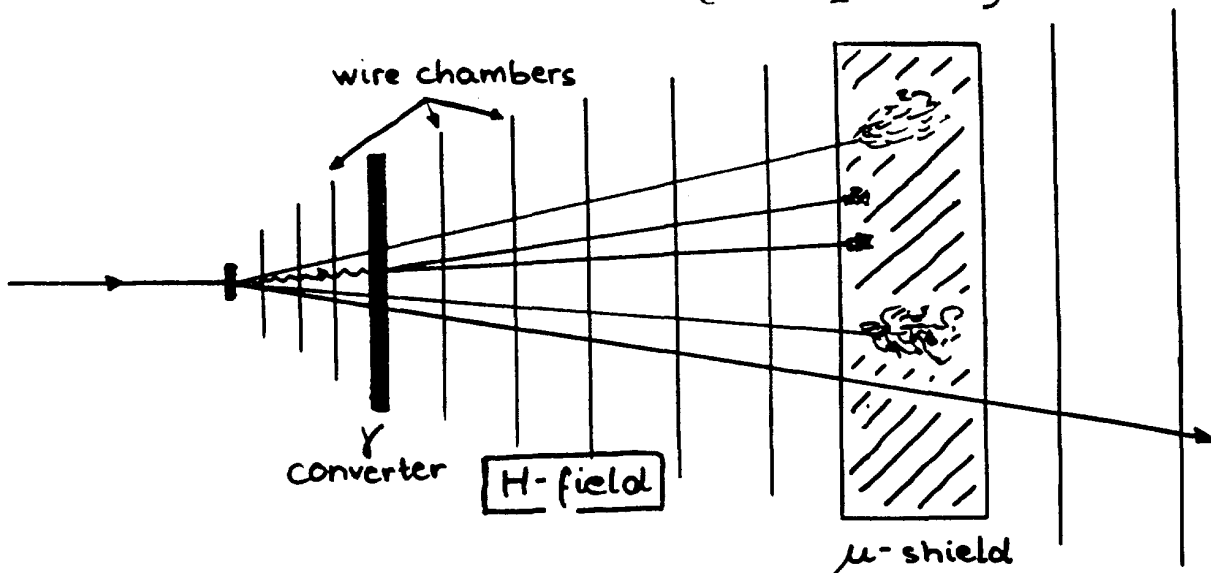
- Experimental particle physics

→ want to measure 4-vectors



METHODS:

- Bubble chamber
- "Electronic" bubble chamber (c, b quarks)



- Calorimetry

IDENTIFICATION OF NEW HADRON IN BUBBLE CHAMBER

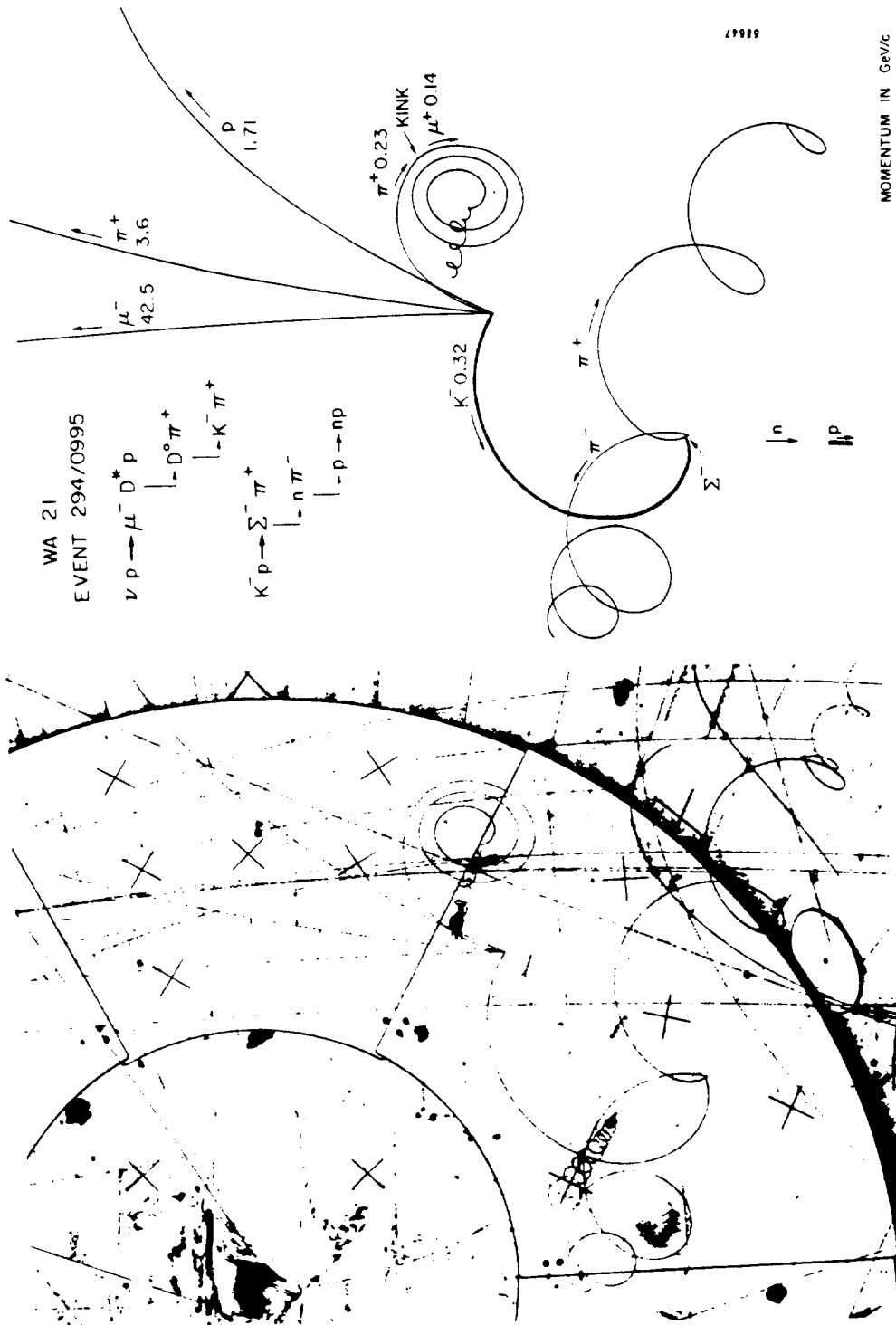


Figure 1

WHAT IS A CALORIMETER?

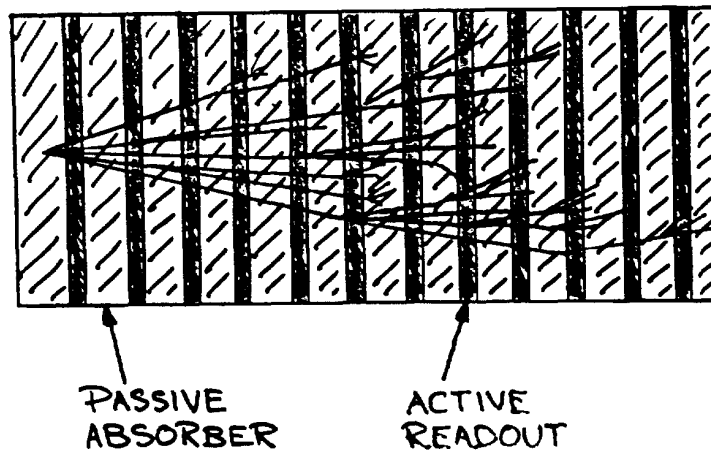
A block of matter ($< 1 \text{ kg} - > 1000 \text{ tons}$) in which the particle gets absorbed, and from which one gets a signal.

Some (constant!?) fraction of the initial particle energy is transformed into a measurable signal, e.g. light or electric charge

The energy resolution is determined by fluctuations in the measured charge.

2 TYPES OF CALORIMETERS:

- Homogeneous calorimeters
- Sampling calorimeters



WHY CALORIMETERS?

→ CALORIMETER PROPERTIES

- Sensitive to charged and neutral particles
- Particle identification ($h/e/\mu/\nu$ separation)
- σ/E improves with increasing E (as c/\sqrt{E} if properly designed)
- Size (\equiv cost) goes as $\log(E)$
- Fast (response times < 100 ns) — high rates
- They don't need a magnetic field
- Granularity → good measurement of particle direction

→ PHYSICS REASONS

- Interest shifted from hadron to quark level → measure jets
- Measure global event properties (E-flow): ΣE_T , E_T^{miss} , E_{tot} , $E_{\text{tot}}^{\text{miss}}$
- Trigger on extremely rare events

Calorimeter performance crucial for experimental successes

Increasingly true at higher energies: SLD, ZEUS, D0, UA1, UA2, HELIOS, H1 spent a major fraction of their budget on calorimetry.

Optimal design → need detailed understanding of factors that limit the calorimeter performance.

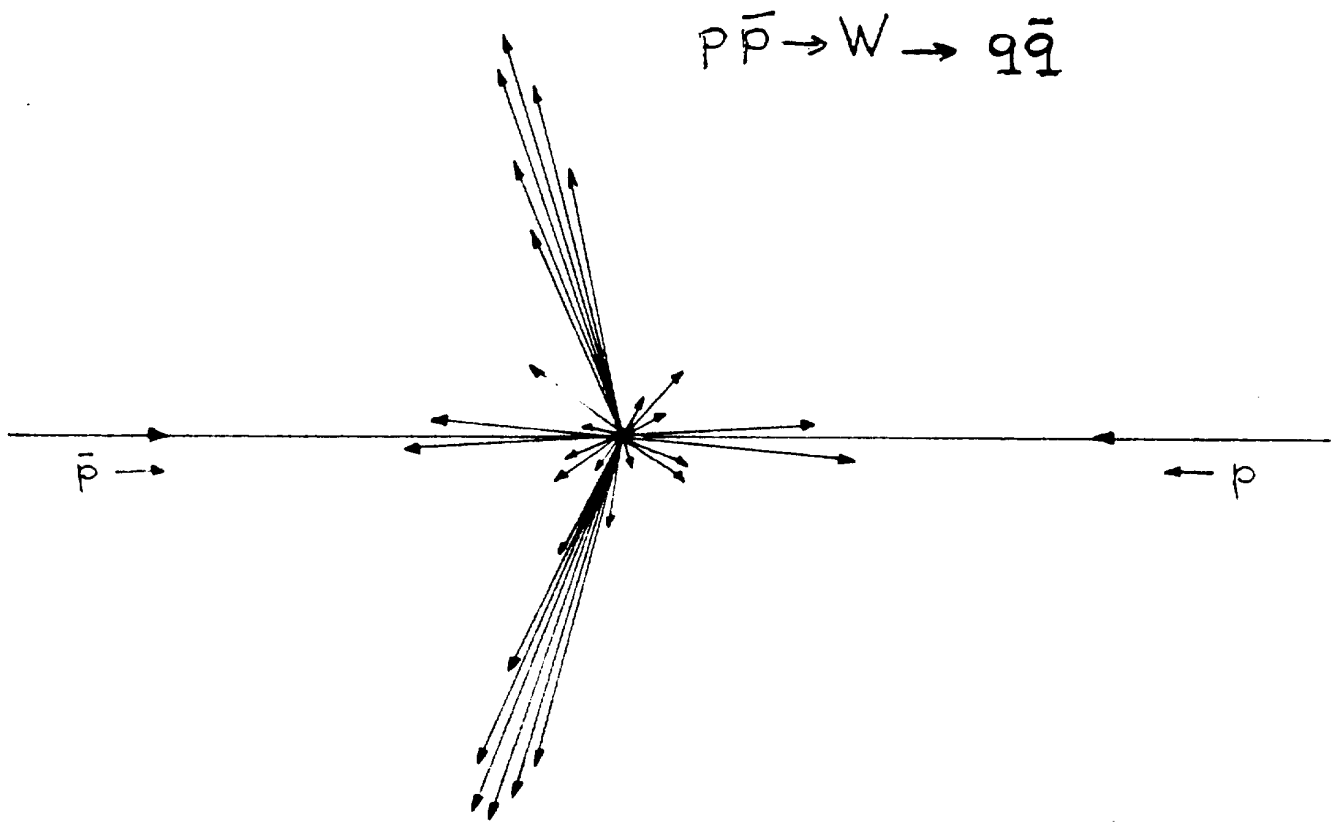


Figure 2

7

RELEVANCE HIGH-RESOLUTION CALORIMETRY AT SUPERCOLLIDERS

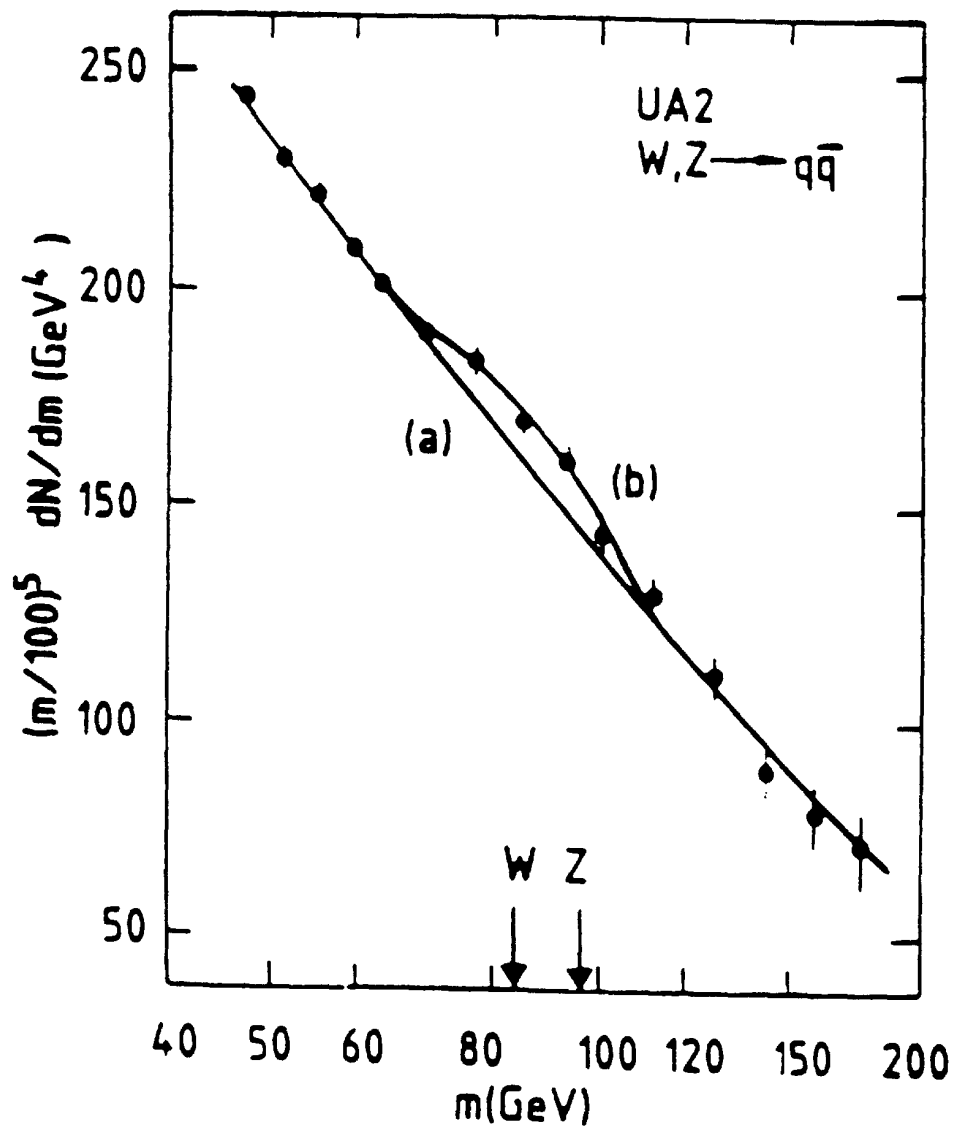


Figure 1

Jet-jet invariant mass distribution, measured in $p\bar{p}$ collisions at $\sqrt{s} = 630\text{GeV}$. Data from ref. 1.

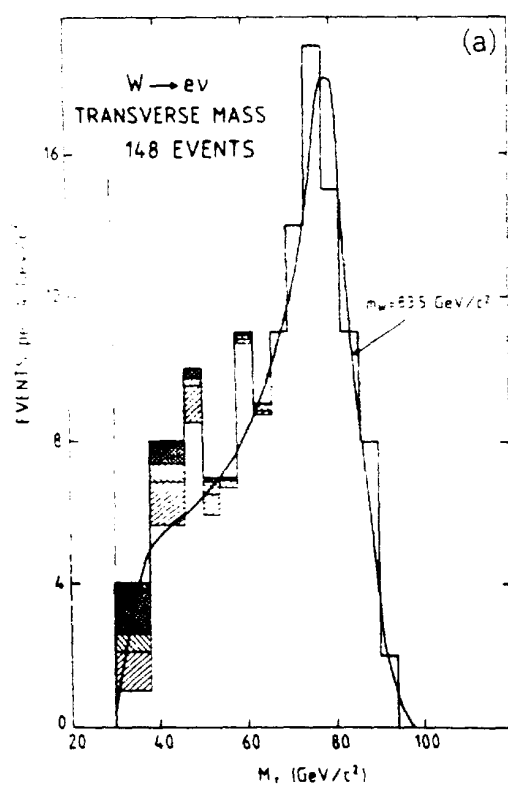
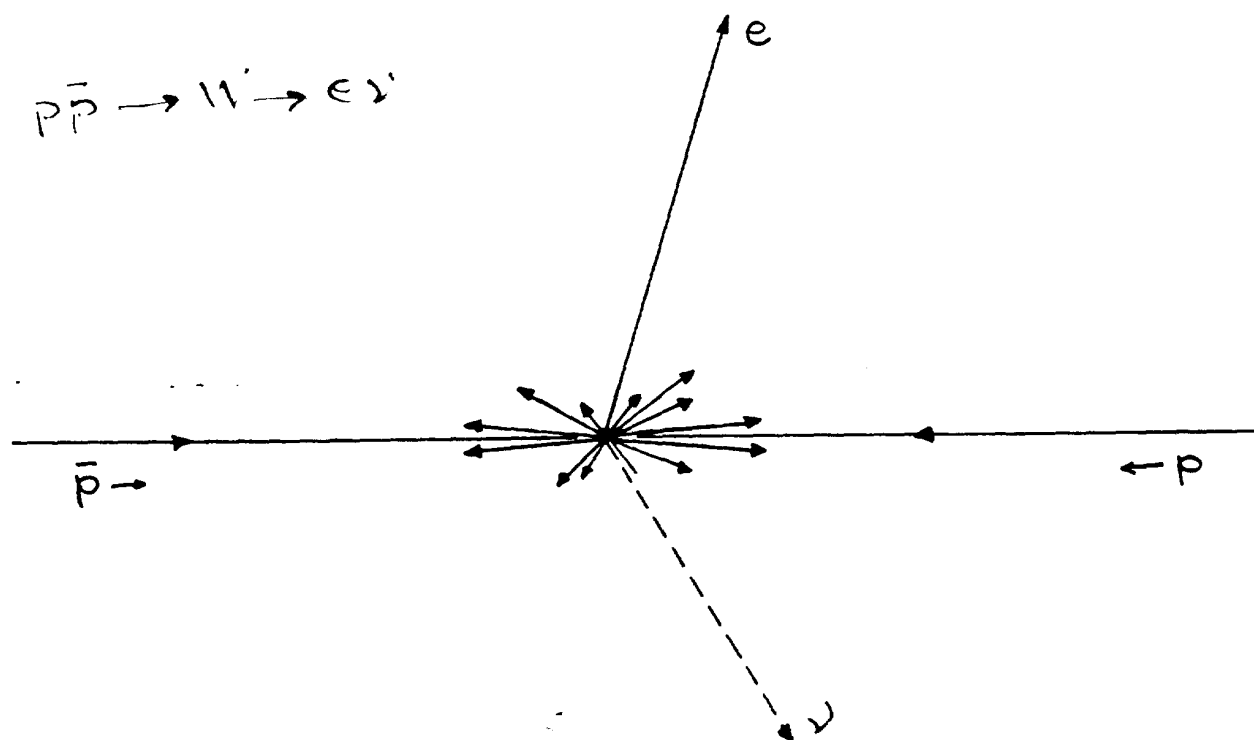


Figure 3

NA 35 $^{16}\text{O} + \text{Pb}$ SEPTEMBER 1986



CERN - SPS E_{SEAM} 3200 GeV

CALORIMETERS FOR DETECTING EM SHOWERS

CALORIMETRY AT VERY LOW ENERGIES

Used by nuclear physicists since more than 50 years (γ detection)

Best results obtained with semiconductor crystals: Ge, Ge(Li), Si(Li)

It takes only ~ 3 eV to create an electron-hole pair

$\rightarrow 350,000/\text{MeV}$, $\rightarrow \sigma/E = \frac{\sqrt{350,000}}{350,000} = 0.17\%$ at 1 MeV

Confirmed in practice

$$\sigma/E = c/\sqrt{E} \text{ for these devices}$$

Already at these very low energies we may have quite complicated showers

Example illustrates some characteristic aspects of calorimetry:

- Shower development
- Effect of fluctuations on the signal distribution
- Leakage

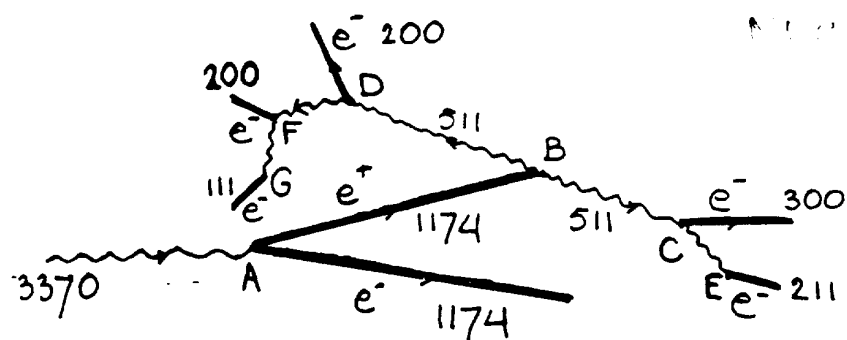
Figure 1 displays three stacked gamma-ray spectra of the ^{99}Ru - ^{99}Mo - ^{94}Tc system. The x-axis represents the channel number, ranging from 400 to 4000. The y-axis represents the count rate, ranging from 10^1 to 10^4 . The spectra show various peaks corresponding to different isotopes and their decay products. Key peaks are labeled with their energy values in keV.

Top Spectrum (400-1000 channels):

- ^{99}Ru peaks: 561, 642, 680, 714, 725, 780, 942, 944, 946, 948, 950, 952, 954, 956, 958, 960, 962, 964, 966, 968, 970, 972, 974, 976, 978, 980, 982, 984, 986, 988, 990, 992, 994, 996, 998, 1000.
- ^{99}Mo peaks: 1023, 1025, 1027, 1029, 1031, 1033, 1035, 1037, 1039, 1041, 1043, 1045, 1047, 1049, 1051, 1053, 1055, 1057, 1059, 1061, 1063, 1065, 1067, 1069, 1071, 1073, 1075, 1077, 1079, 1081, 1083, 1085, 1087, 1089, 1091, 1093, 1095, 1097, 1099, 1101, 1103, 1105, 1107, 1109, 1111, 1113, 1115, 1117, 1119, 1121, 1123, 1125, 1127, 1129, 1131, 1133, 1135, 1137, 1139, 1141, 1143, 1145, 1147, 1149, 1151, 1153, 1155, 1157, 1159, 1161, 1163, 1165, 1167, 1169, 1171, 1173, 1175, 1177, 1179, 1181, 1183, 1185, 1187, 1189, 1191, 1193, 1195, 1197, 1199, 1201, 1203, 1205, 1207, 1209, 1211, 1213, 1215, 1217, 1219, 1221, 1223, 1225, 1227, 1229, 1231, 1233, 1235, 1237, 1239, 1241, 1243, 1245, 1247, 1249, 1251, 1253, 1255, 1257, 1259, 1261, 1263, 1265, 1267, 1269, 1271, 1273, 1275, 1277, 1279, 1281, 1283, 1285, 1287, 1289, 1291, 1293, 1295, 1297, 1299, 1301, 1303, 1305, 1307, 1309, 1311, 1313, 1315, 1317, 1319, 1321, 1323, 1325, 1327, 1329, 1331, 1333, 1335, 1337, 1339, 1341, 1343, 1345, 1347, 1349, 1351, 1353, 1355, 1357, 1359, 1361, 1363, 1365, 1367, 1369, 1371, 1373, 1375, 1377, 1379, 1381, 1383, 1385, 1387, 1389, 1391, 1393, 1395, 1397, 1399, 1401, 1403, 1405, 1407, 1409, 1411, 1413, 1415, 1417, 1419, 1421, 1423, 1425, 1427, 1429, 1431, 1433, 1435, 1437, 1439, 1441, 1443, 1445, 1447, 1449, 1451, 1453, 1455, 1457, 1459, 1461, 1463, 1465, 1467, 1469, 1471, 1473, 1475, 1477, 1479, 1481, 1483, 1485, 1487, 1489, 1491, 1493, 1495, 1497, 1499, 1501, 1503, 1505, 1507, 1509, 1511, 1513, 1515, 1517, 1519, 1521, 1523, 1525, 1527, 1529, 1531, 1533, 1535, 1537, 1539, 1541, 1543, 1545, 1547, 1549, 1551, 1553, 1555, 1557, 1559, 1561, 1563, 1565, 1567, 1569, 1571, 1573, 1575, 1577, 1579, 1581, 1583, 1585, 1587, 1589, 1591, 1593, 1595, 1597, 1599, 1601, 1603, 1605, 1607, 1609, 1611, 1613, 1615, 1617, 1619, 1621, 1623, 1625, 1627, 1629, 1631, 1633, 1635, 1637, 1639, 1641, 1643, 1645, 1647, 1649, 1651, 1653, 1655, 1657, 1659, 1661, 1663, 1665, 1667, 1669, 1671, 1673, 1675, 1677, 1679, 1681, 1683, 1685, 1687, 1689, 1691, 1693, 1695, 1697, 1699, 1701, 1703, 1705, 1707, 1709, 1711, 1713, 1715, 1717, 1719, 1721, 1723, 1725, 1727, 1729, 1731, 1733, 1735, 1737, 1739, 1741, 1743, 1745, 1747, 1749, 1751, 1753, 1755, 1757, 1759, 1761, 1763, 1765, 1767, 1769, 1771, 1773, 1775, 1777, 1779, 1781, 1783, 1785, 1787, 1789, 1791, 1793, 1795, 1797, 1799, 1801, 1803, 1805, 1807, 1809, 1811, 1813, 1815, 1817, 1819, 1821, 1823, 1825, 1827, 1829, 1831, 1833, 1835, 1837, 1839, 1841, 1843, 1845, 1847, 1849, 1851, 1853, 1855, 1857, 1859, 1861, 1863, 1865, 1867, 1869, 1871, 1873, 1875, 1877, 1879, 1881, 1883, 1885, 1887, 1889, 1891, 1893, 1895, 1897, 1899, 1901, 1903, 1905, 1907, 1909, 1911, 1913, 1915, 1917, 1919, 1921, 1923, 1925, 1927, 1929, 1931, 1933, 1935, 1937, 1939, 1941, 1943, 1945, 1947, 1949, 1951, 1953, 1955, 1957, 1959, 1961, 1963, 1965, 1967, 1969, 1971, 1973, 1975, 1977, 1979, 1981, 1983, 1985, 1987, 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, 2009, 2011, 2013, 2015, 2017, 2019, 2021, 2023, 2025, 2027, 2029, 2031, 2033, 2035, 2037, 2039, 2041, 2043, 2045, 2047, 2049, 2051, 2053, 2055, 2057, 2059, 2061, 2063, 2065, 2067, 2069, 2071, 2073, 2075, 2077, 2079, 2081, 2083, 2085, 2087, 2089, 2091, 2093, 2095, 2097, 2099, 2101, 2103, 2105, 2107, 2109, 2111, 2113, 2115, 2117, 2119, 2121, 2123, 2125, 2127, 2129, 2131, 2133, 2135, 2137, 2139, 2141, 2143, 2145, 2147, 2149, 2151, 2153, 2155, 2157, 2159, 2161, 2163, 2165, 2167, 2169, 2171, 2173, 2175, 2177, 2179, 2181, 2183, 2185, 2187,

Figure 6

SHOWER DEVELOPMENT BY MULTIPLE X'S



LEAKAGE

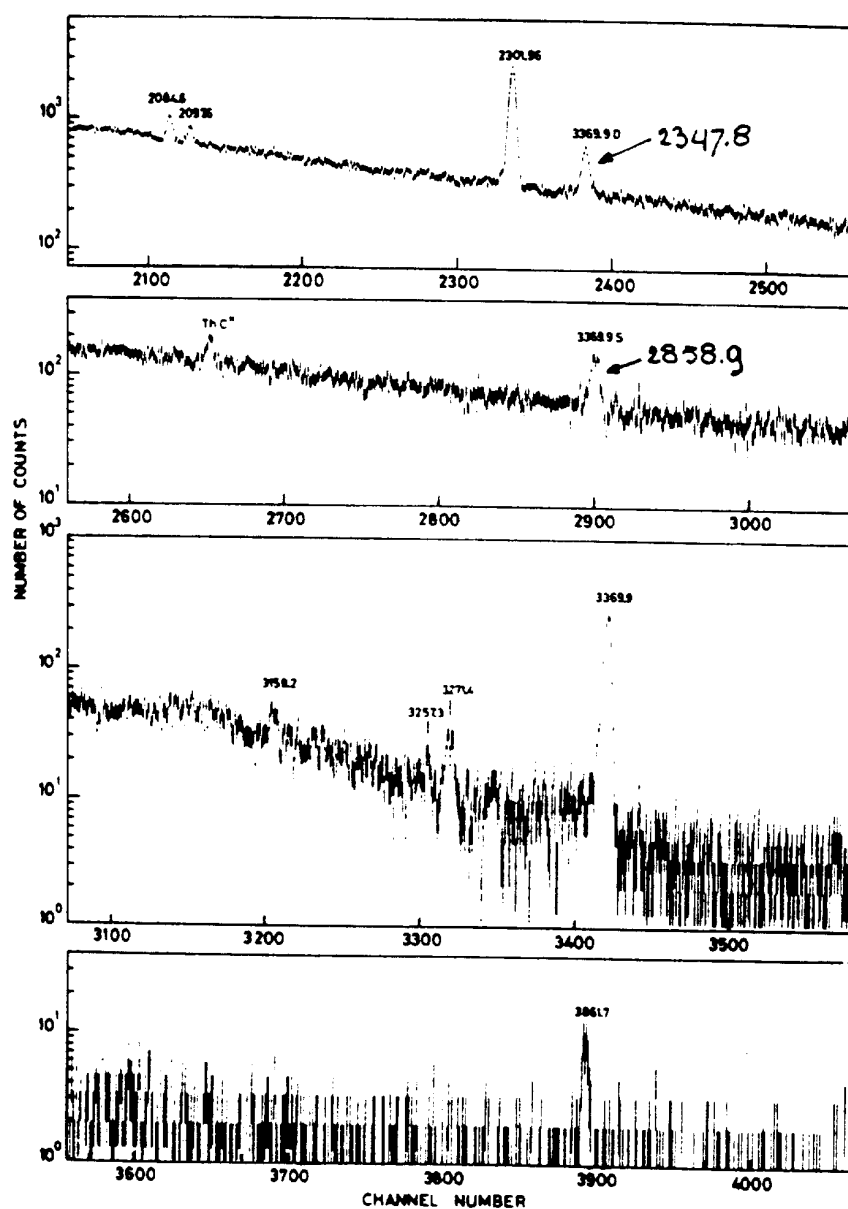
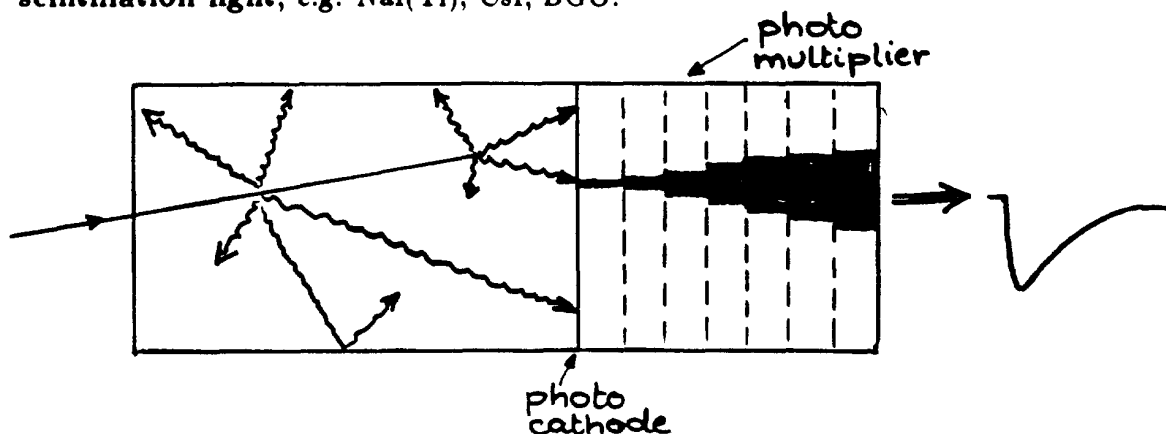


Figure 7

SCINTILLATION COUNTERS

Other nuclear γ detectors are based on the detection of scintillation light, e.g. NaI(Tl), CsI, BGO.



COMPLICATIONS COMPARED TO SEMICONDUCTOR CRYSTALS:

- Scintillation light spectrum
- Sensitivity photocathode
- Light isotropically emitted \rightarrow losses

\rightarrow Signal fluctuations do not only depend on statistics in primary processes (emission scintillation light), but also on e.g.

- What kind of light is produced
- Where is it produced

Fluctuations largely E -independent $\rightarrow \boxed{\sigma/E \neq c/\sqrt{E}}$

EXPERIMENTAL RESULTS:

8 keV $\rightarrow \sigma/E \approx 15\%$ (200 eV/p.e.)

1 MeV $\rightarrow \sigma/E \approx 5\%$

MECHANISMS OF ENERGY LOSS IN HIGH-ENERGY EM SHOWERS

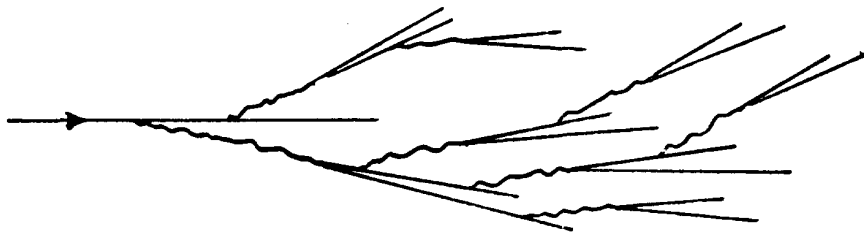
eV, keV, MeV \rightarrow GeV, TeV ($1 \text{ cal} \approx 2.6 \cdot 10^7 \text{ TeV}$)

ALREADY SEEN:

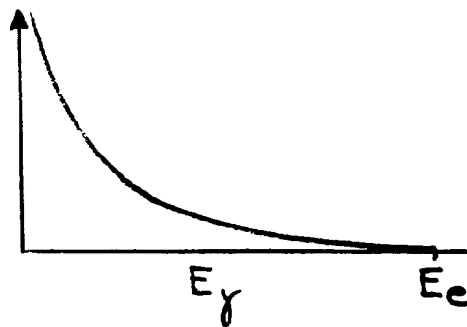
- Ionization for e^+ , e^-
- $\gamma \rightarrow e^+e^-$
- Compton scattering $\gamma \rightarrow e^- + \gamma'$
- Photo-electric effect $\gamma \rightarrow e^-$

At high energies one new process: Bremsstrahlung

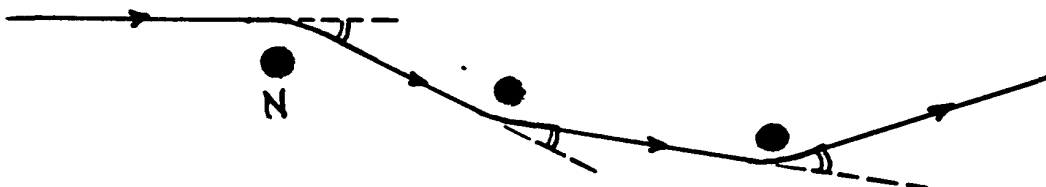
$e \rightarrow e' + \gamma$ in nuclear Coulomb field \rightarrow Particle multiplication



- Bremsstrahlung principle source of energy loss high-E electrons
- Bremsstrahlung spectrum soft



- Multiple scattering



PART OF AN EM SHOWER RECORDED IN A
BUBBLE CHAMBER



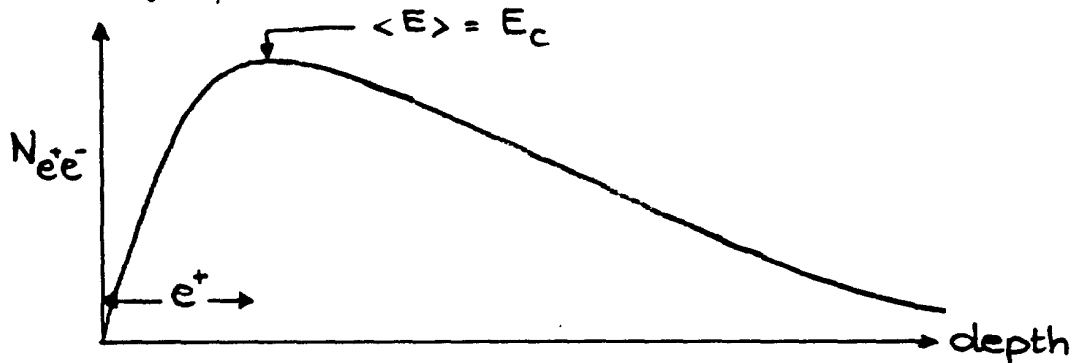
- overwhelming majority shower particles very soft
- $\langle E \rangle$ shower particles decreases in time (depth)

EM SHOWER DEVELOPMENT

- Governed by laws of QED
- Electron density in matter $\sim Z$

CRITICAL ENERGY \rightarrow shower particle multiplication stopped

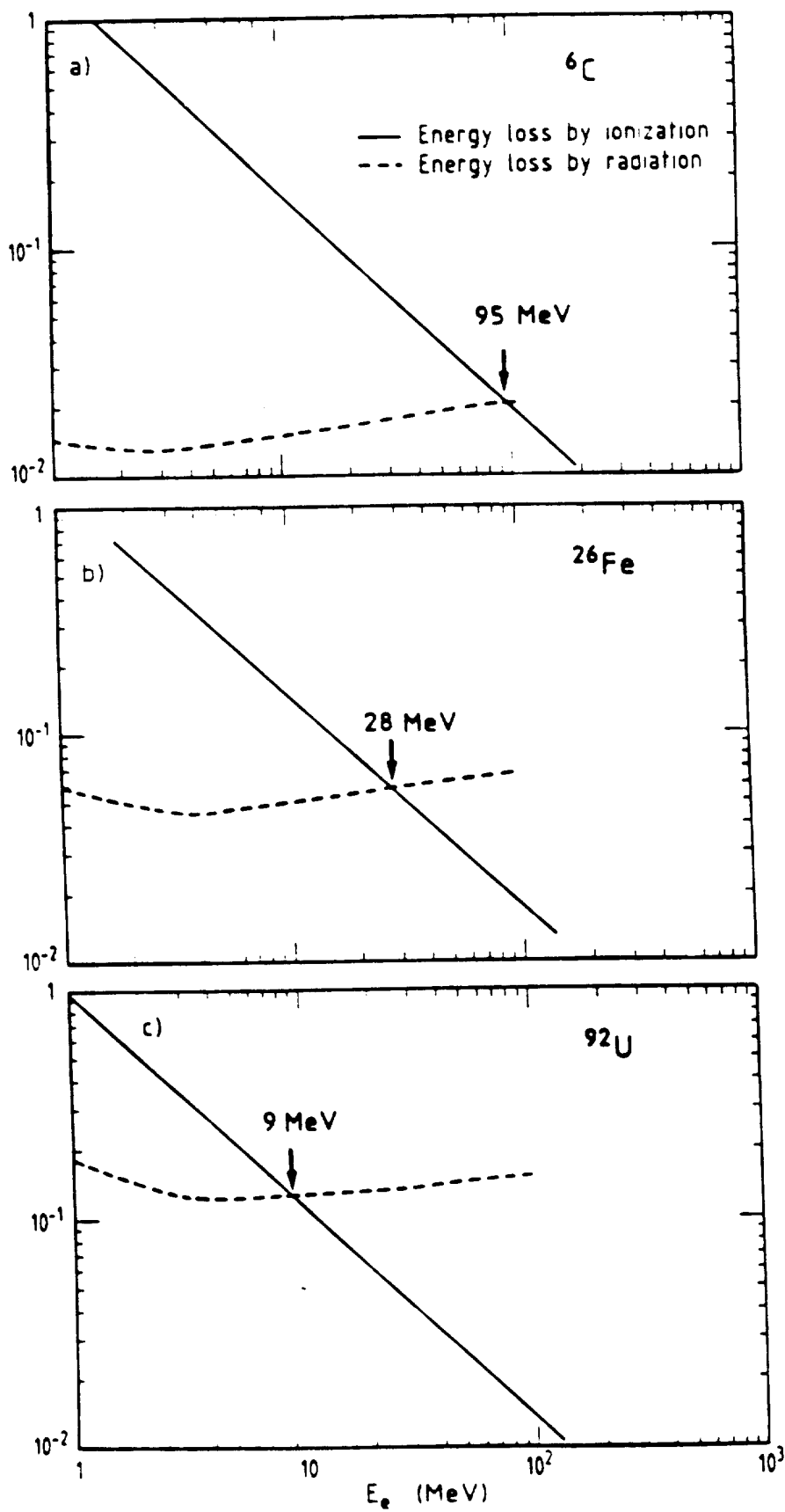
- $E > E_c$: $\gamma \rightarrow e^+e^-$, $e \rightarrow e' + \gamma$
- $E < E_c$: $\gamma \rightarrow e^-$, e stopped.
- $E_c \sim 1/Z$



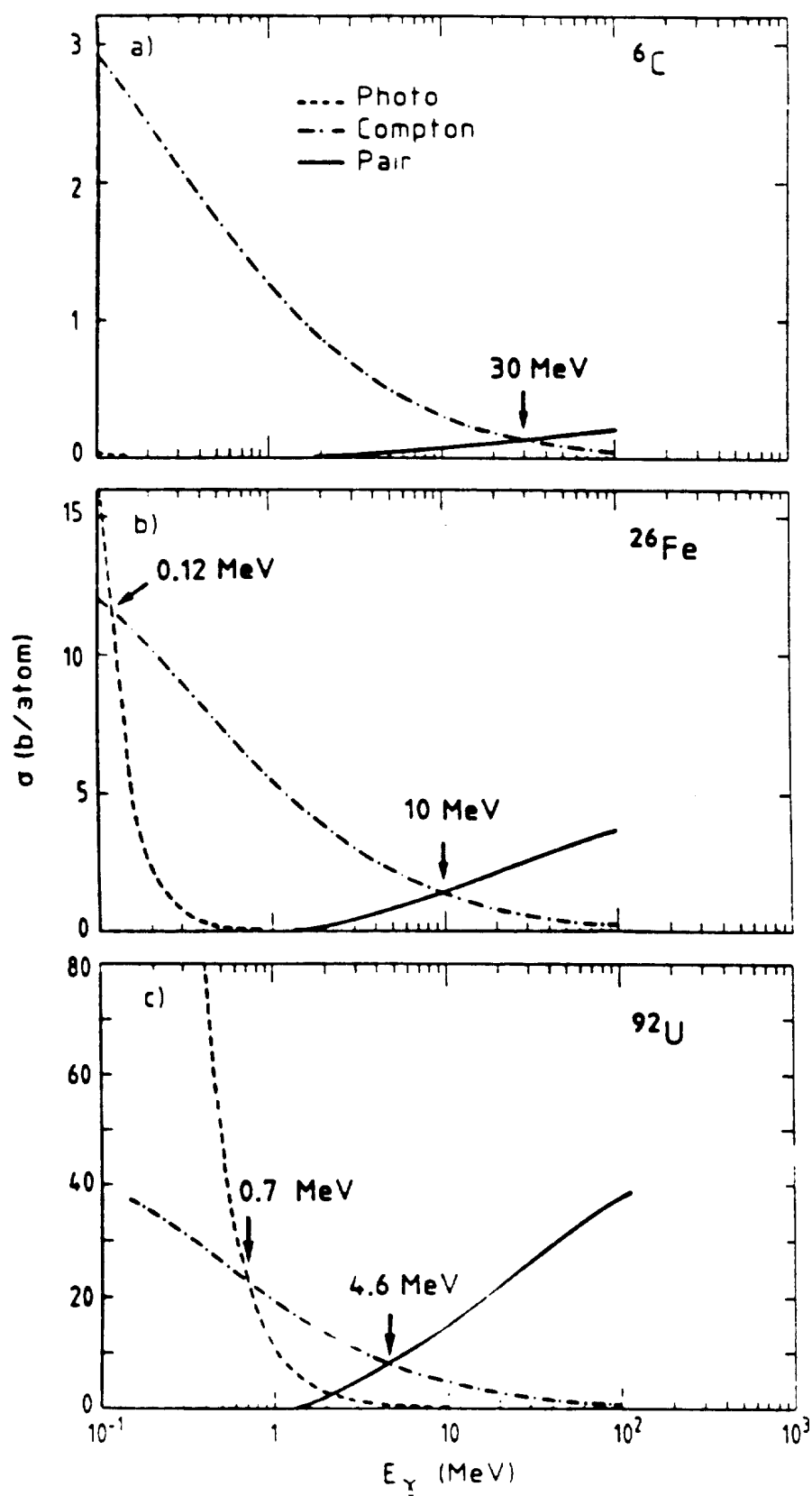
- Number of different shower particles increases with Z
- $\gamma \rightarrow e^+e^-$ continues until lower energies
- $e \rightarrow e'\gamma$ continues until lower energies.

Physics of em shower development well-understood and relatively simple
 \rightarrow Monte Carlo simulations reliable: EGS 4

ENERGY LOSS e^\pm



CROSS SECTIONS FOR PHOTONS



EM SHOWER CHARACTERISTICS

MATERIAL-INDEPENDENT DESCRIPTION

Shower dimensions scale with:

- Radiation length X_0 (longitudinal)
- Molière radius ρ_M (radial)

$$X_0 \approx 180 A/Z^2 \text{g/cm}^2 \quad \rho_M \approx 7 A/Z \text{g/cm}^2$$

Scaling in X_0 and ρ_M approximately correct

Deviations due to low- E peculiarities (X_0 defined at $E = \infty$)

Reasonable fit: $N = N_0 X_0^a \exp(-b X_0)$, $a, b = f(Z)$, $a = f(E)$

Shower max: $a/b \sim \log(E)$

CONTAINMENT:

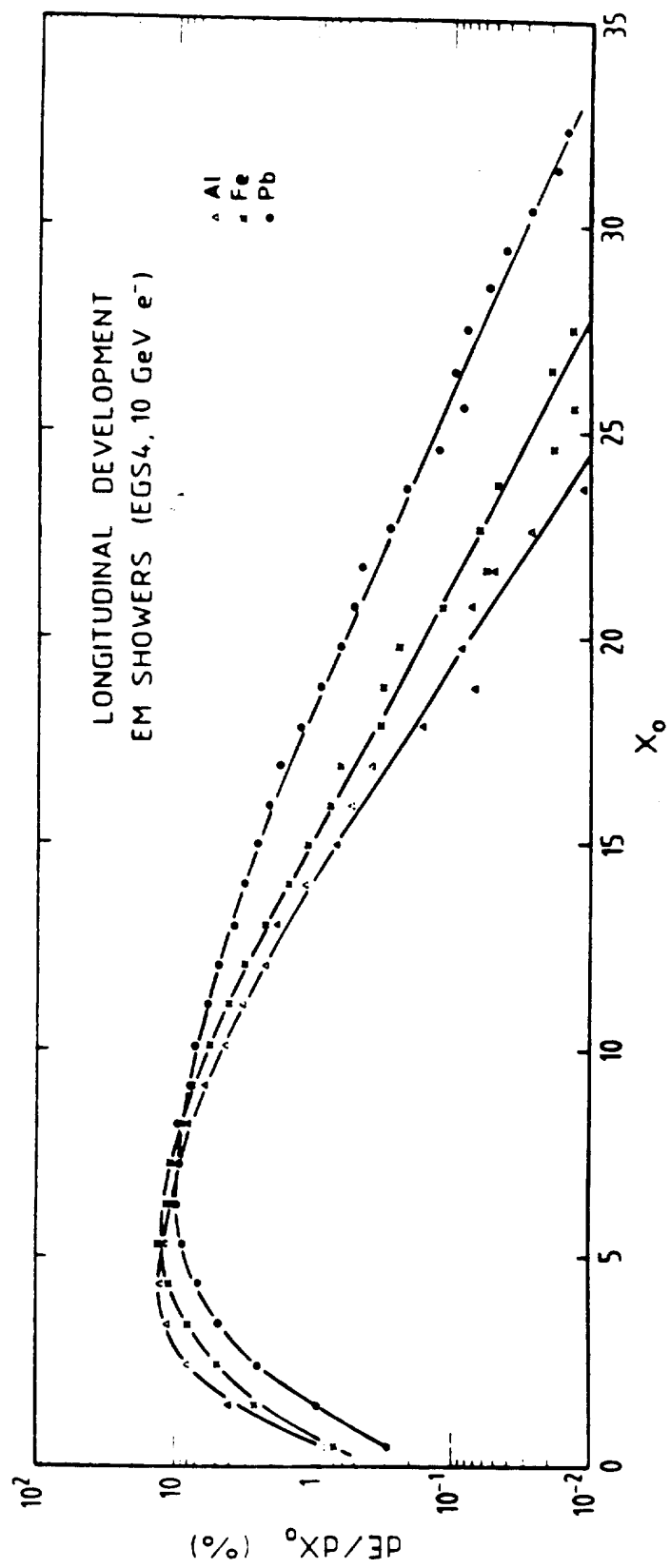
- 10 GeV \rightarrow 25 X_0 for 99%
- 20 GeV \rightarrow only 1.3 X_0 extra!

\rightarrow Need ~ 15 cm Pb to contain 20 GeV γ showers

- Need more for 1 Curie ^{60}Co source (1 MeV γ 's)

X_0 has no meaning for low energies. Low-energy gammas may easily travel many radiation lengths, especially in high- Z materials

LONGITUDINAL DEVELOPMENT EM SHOWERS



LATERAL SHOWER SPREAD

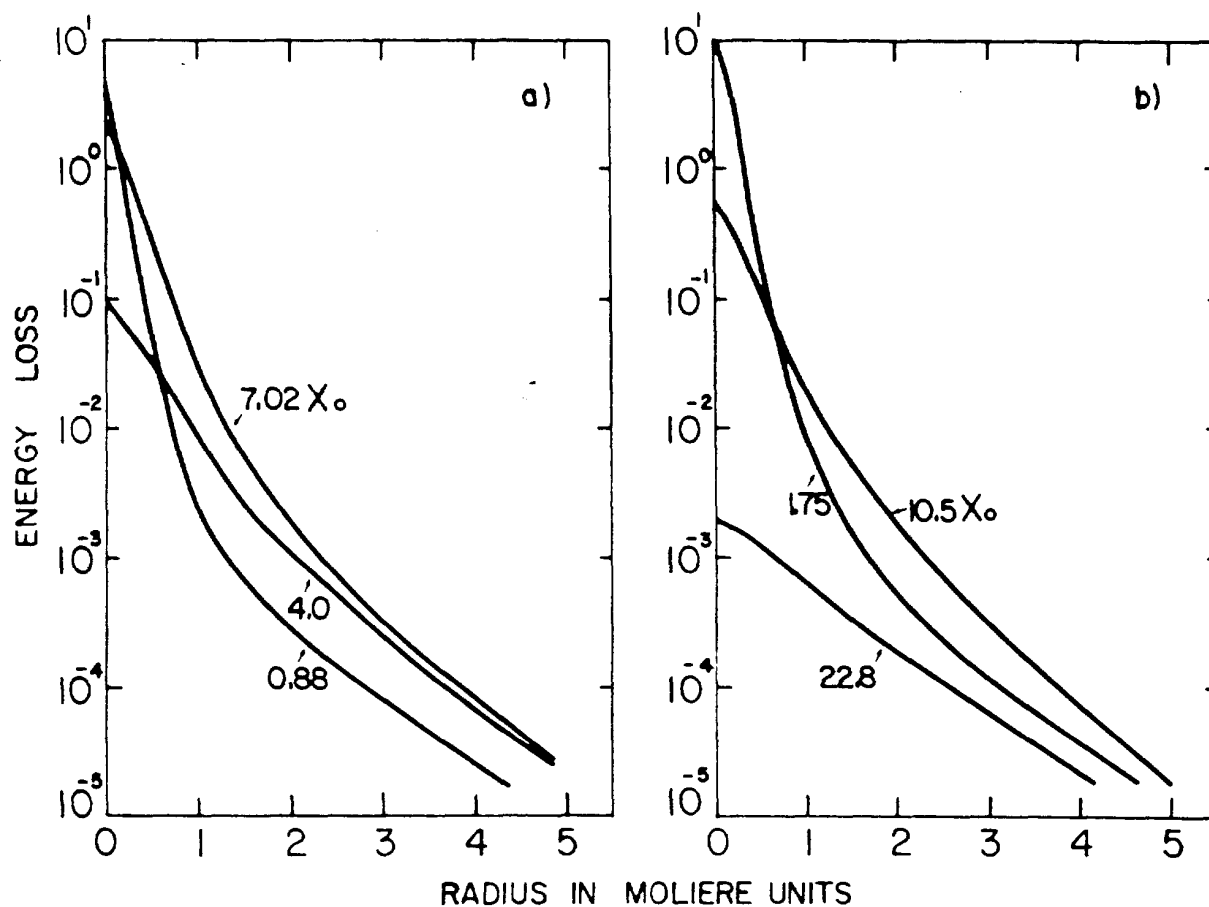
2 EFFECTS:

a) Multiple scattering electrons

b) γ 's around 1 MeV may travel many X_0

- (a) dominates before shower maximum
- 2 components clearly visible (Pb)
- (b) much less important at low Z \rightarrow shower more narrow (in ρ_M)
- Very good position resolution in first few X_0 ($\leq 1\text{mm}$)

LATERAL DEVELOPMENT EM SHOWERS



1 GeV e^- in Pb
 $r_M(\text{Pb}) = 1.7 \text{ cm}$

Figure 12

THE ENERGY RESOLUTION OF EM CALORIMETERS

HOMOGENEOUS (FULLY SENSITIVE) DEVICES:

- NaI(Tl): 60 cm ($24 X_0$) crystal $\rightarrow \sigma/E = 0.9\%$ at 1 GeV.

Limit: Fluctuations in light collection, not production

- BGO ($X_0 = 1.1$ cm): Similar properties
- Lead Glass: Detection Čerenkov light.

If $E_e > 0.7$ MeV \rightarrow Čerenkov light, ~ 1400 photons/GeV.

Č-light directional \rightarrow good collection efficiency.

At 1 GeV: $\sigma/E \sim \sqrt{700}/700 \sim 5\% \rightarrow \sigma/E \sim 5\%/\sqrt{E} [\text{GeV}^{-1/2}]$

Energy resolution limited by fluctuations shower development

SAMPLING CALORIMETERS:

- Measure energy loss charged shower particles in active layers
- Which fraction of E? Mass ratio active/passive (rough estimate)
- Solid or liquid active layers: 1-10%, gases: $10^{-4} - 10^{-5}$

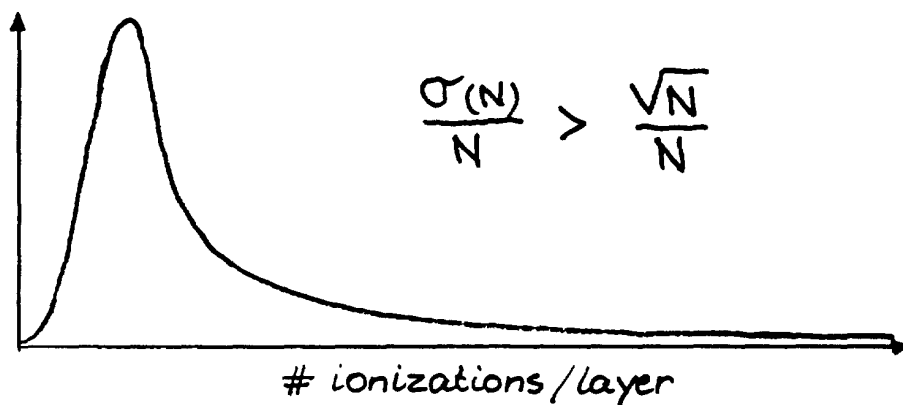
THE ENERGY RESOLUTION OF EM SAMPLING CALORIMETERS

All sampling calorimeters based on abundant primary processes

(scintillation, ionisation charge collection, $> 10^6/\text{GeV}$)

Nevertheless, (photo-)electron statistics may contribute to σ/E :

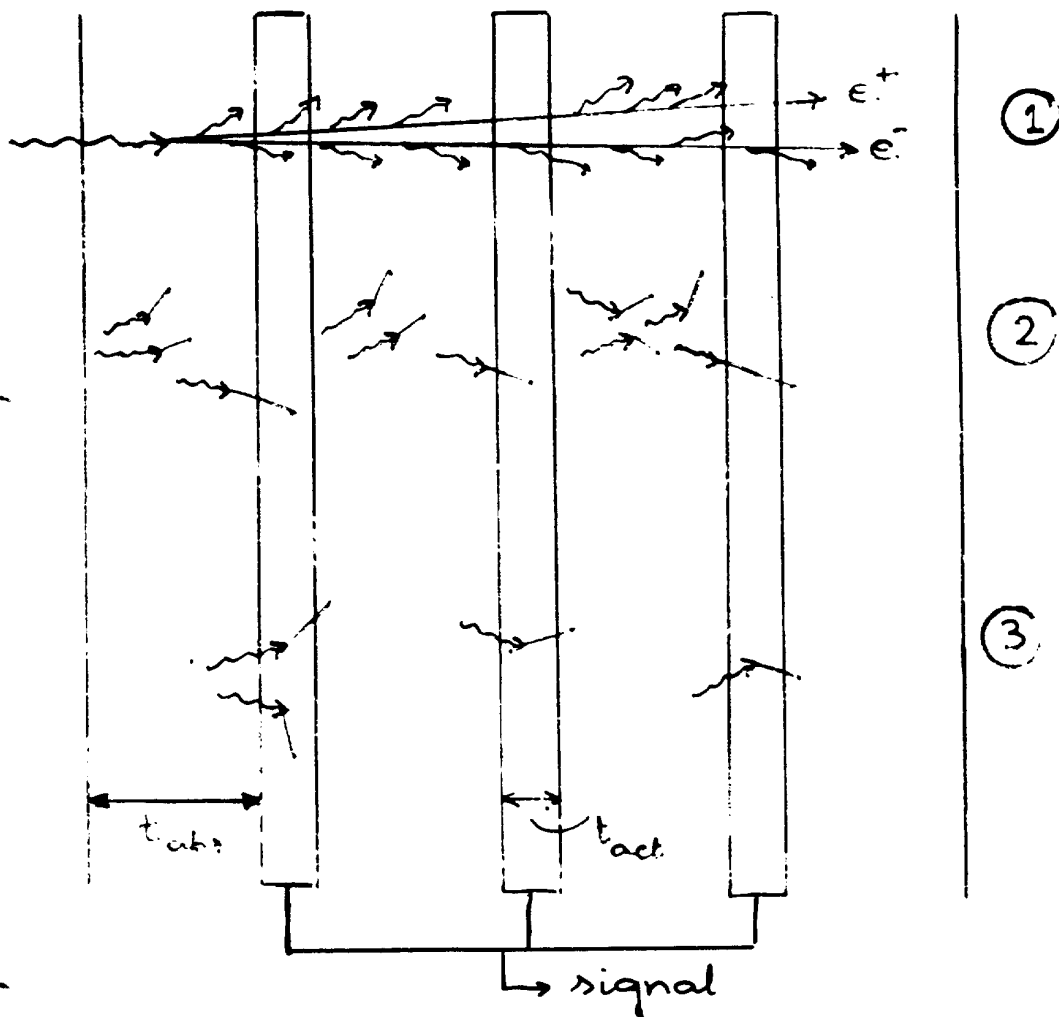
- Scintillator: 1000 p.e/GeV is very good $\rightarrow 3\%/\sqrt{E}$ from photon statistics.
- Wire chambers: 10^{-4} sampling fraction $\rightarrow 100$ ionizations per GeV in active layers $\rightarrow 10\%/\sqrt{E}$ contribution to σ/E
- In addition, Landau fluctuations



Major contribution to resolution of sampling calorimeters comes from fluctuations in the number of shower particles contributing to signal: Sampling fluctuations

ANALYSIS SAMPLING FLUCTUATIONS

Distinguish 3 types of contributions



- ① Fluctuations determined by $\sqrt{A/\tau}$
 Only dependent on t_{obs} if $t_{obs} > 1\%$ ($\sigma_{SAMP}/E = c\sqrt{t_{obs}}$)
 Independent on t_{act}

- ② $\sigma_{SAMP}/E = c\sqrt{t_{obs}}$
 Independent on t_{act}

- ③ $\sigma_{SAMP}/E = c\sqrt{t_{obs}}$ for fixed t_{act}
 $\sigma_{SAMP}/E = c/\sqrt{t_{act}}$ for fixed t_{obs}

ANALYSIS SAMPLING FLUCTUATIONS

EGS 4 \rightarrow ②+③ dominating: WHY?

- Only $\sim 65 \text{ } e^+$ produced per GeV in U, less for low-Z
- Electrons softer than 1 MeV deposit 25 – 40% of ionisation energy (Compton, photo-electrons) $\rightarrow > 1000/\text{GeV}!$

N.B. Most of these electrons are not detected because of their short range (in U: 0.4 mm at 1 MeV, 0.02 mm at 0.1 MeV)

Relative contribution ② and ③ strongly dependent on configuration

- Fe/LAr \rightarrow ③ dominates
- Gas calorimeters \rightarrow No contribution from ③ Much less particles contribute to signal \rightarrow larger fluctuations
- High-Z calorimeters \rightarrow ③ suppressed by photo-electric effect ($\sim Z^5$) \rightarrow resolution worse than for Fe at same sampling fraction.

ENERGY DEPOSIT IN 10 GeV e^- SHOWER (EGS 4)

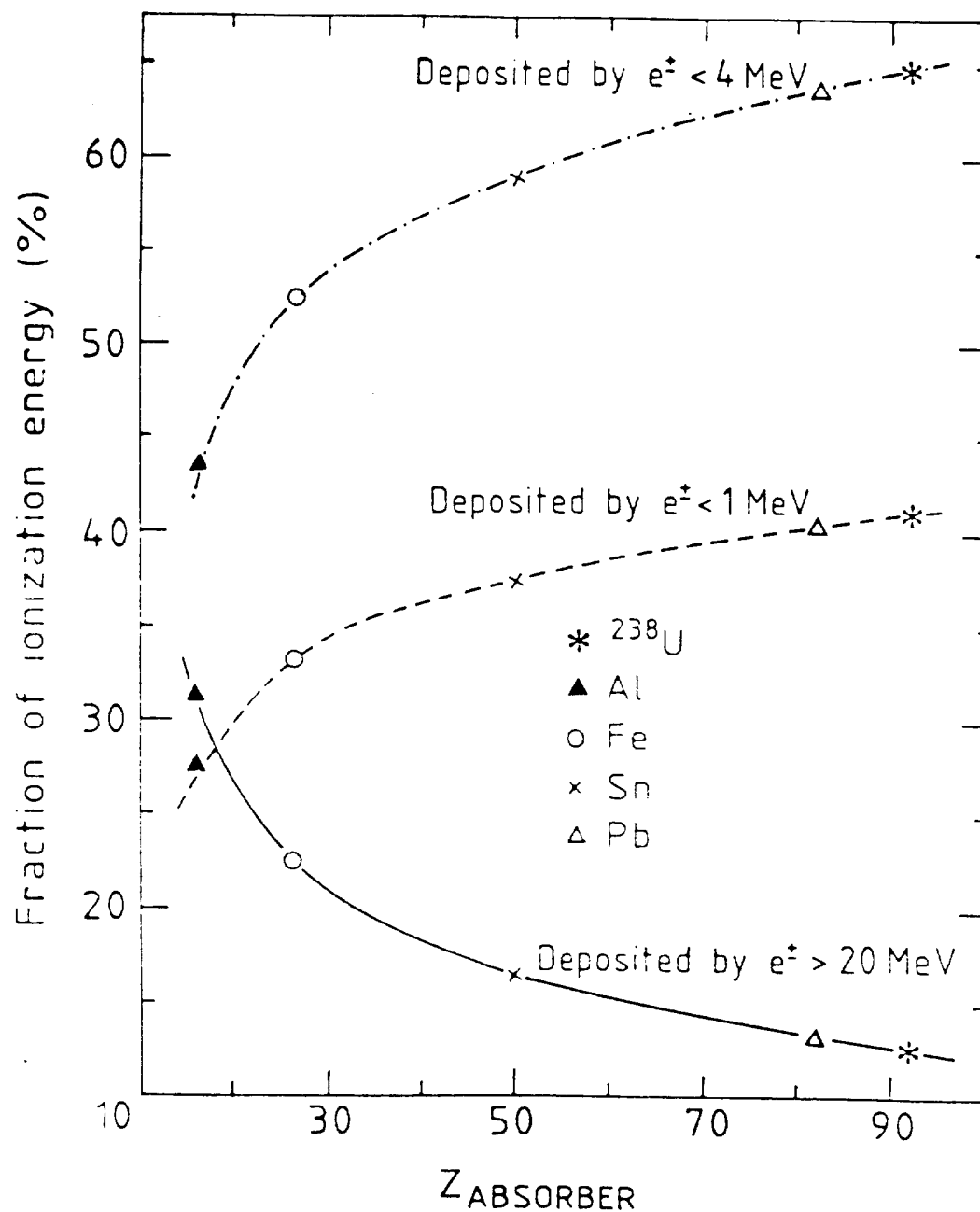


Figure 13

RESOLUTION Fe/LAr em SHOWERS

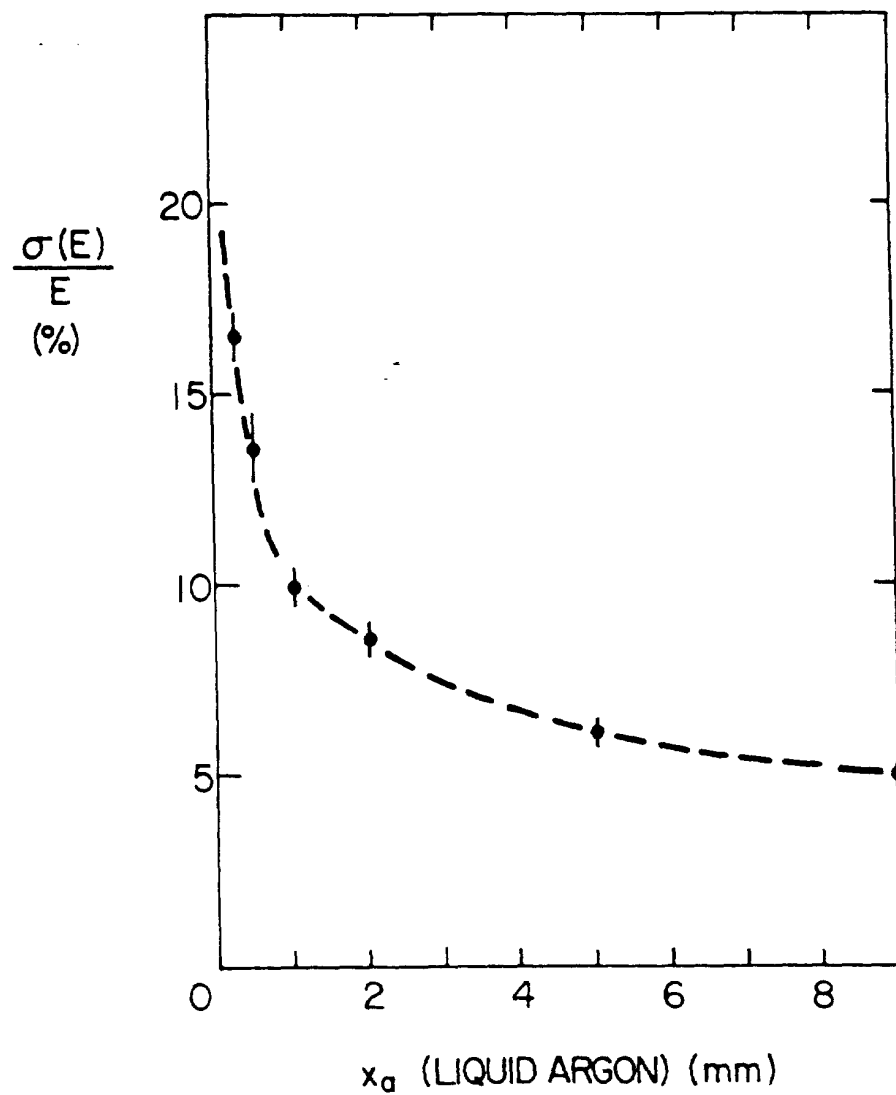


Figure 14

RESOLUTION em SHOWERS

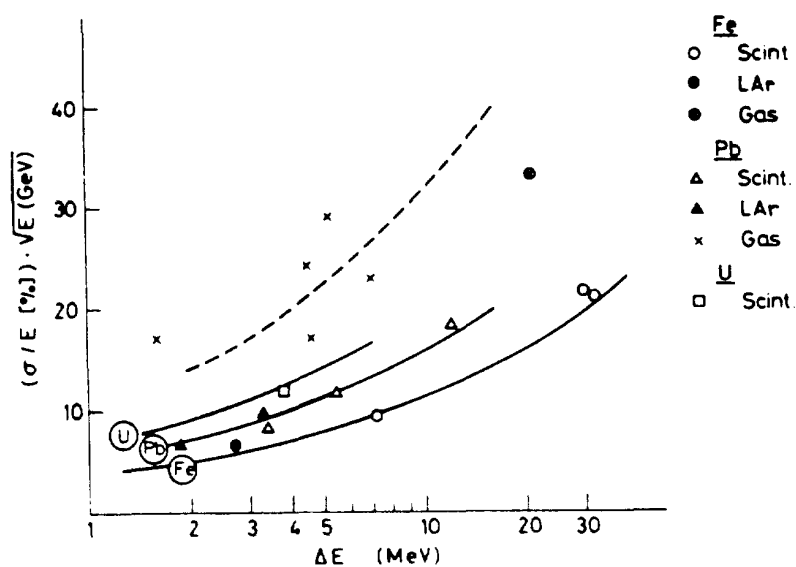


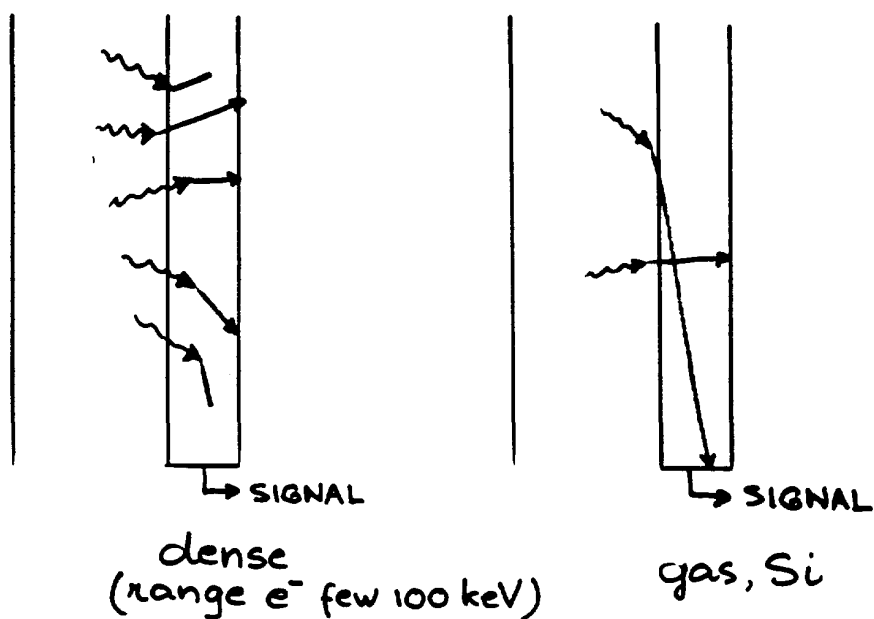
Figure 15

PATH LENGTH FLUCTUATIONS

More refined analysis of em calorimeter energy resolution

Fluctuations in amount of energy deposited by individual particles

Angular distribution → Path length fluctuations



Contribution depends on range of typical electrons contributing to signal, compared to the thickness of the active layers

RESOLUTION EM SHOWERS IN Pb/gas

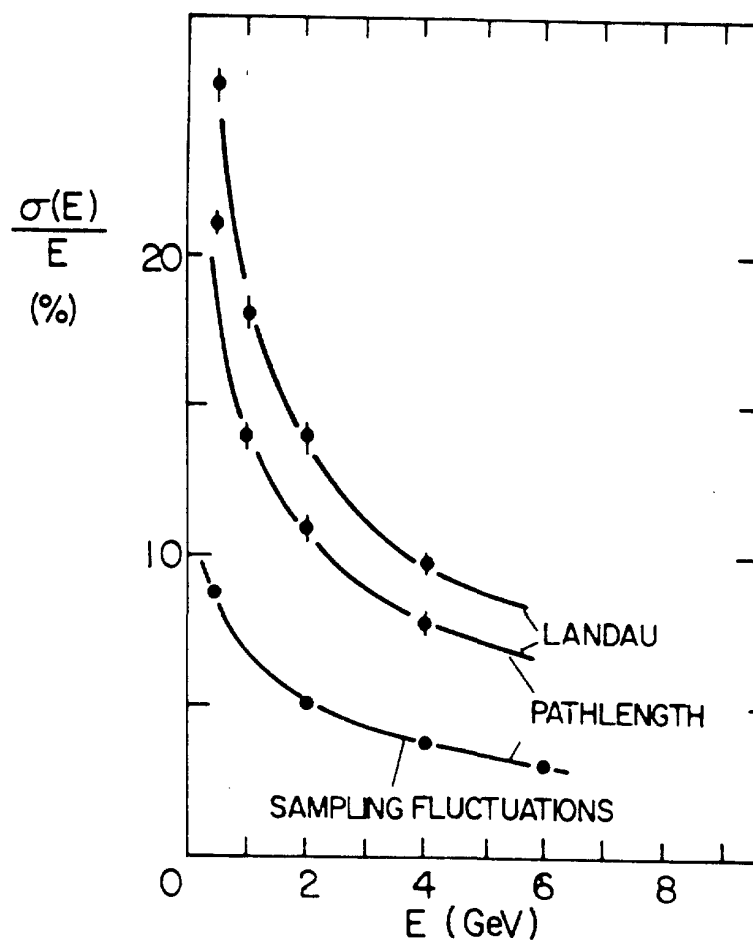


Figure 16

SUMMARY YESTERDAY

WHY CALORIMETRY?

- Calorimeter properties (high E)
- Physics (E-flow)

CALORIMETERS FOR DETECTING EM SHOWERS

- Nuclear energies: $\sigma/E = c/\sqrt{E}$?
- Mechanisms of energy loss
- Dimensions of em showers (X_0 , ρ_M)

Deviations scaling \rightarrow low-energy phenomena

- Energy resolution em calorimeters

Homogeneous calorimeters: \dot{C} vs scintillation light

Sampling calorimeters: σ/E dominated by fluctuations in number of particles. Very configuration-dependent.

READOUT TECHNIQUES FOR SAMPLING CALORIMETERS

Chosen solution depends on performance requirements + cost

REQUIREMENTS USUALLY CONCERN:

- Energy resolution
- Signal linearity + line shape
- Electron/pion separation
- Position resolution (granularity)
- Hermeticity
- Rate capability
- Radiation resistance
- Signal uniformity
- Electronic stability + calibration
- Operation in a magnetic field
- Compactness

READOUT TECHNIQUES SAMPLING CALORIMETERS

Plastic Scintillator

HELIOS, ZEUS, UA2, CDF (all using WLS readout)

ADVANTAGES SCINTILLATOR:

- Minimizes dead space (hermetic)
- Compact construction
- Easy (cheap) technology
- Fast → high rate capability

DISADVANTAGES SCINTILLATOR:

- Granularity
- Signal uniformity
- Radiation sensitivity
- Stability (PM)

- Interesting new development: Scintillating plastic fibres

READOUT TECHNIQUES FOR SAMPLING CALORIMETERS

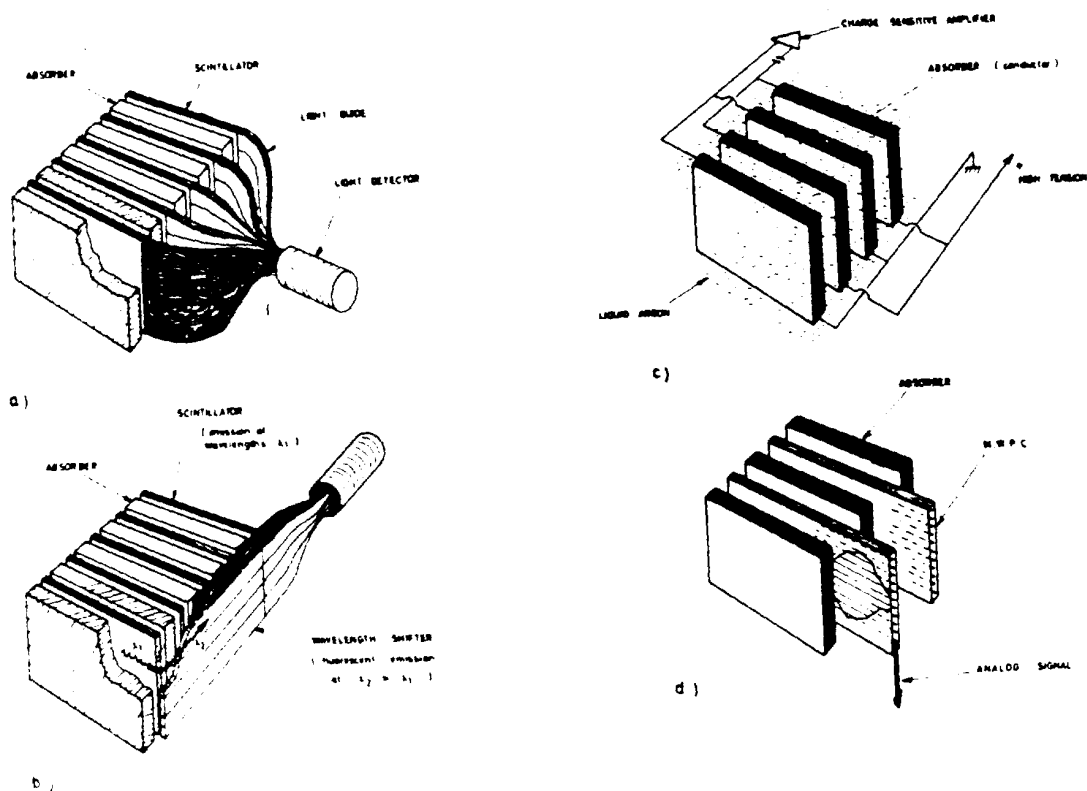


Figure 17

READOUT TECHNIQUES SAMPLING CALORIMETERS

CHARGE COLLECTING DEVICES (solids, liquids, gases)

Silicon

(not yet applied in large scale experiment)

ADVANTAGES:

- | |
|-------------------|
| • Compactness |
| • Granularity |
| • Rate capability |
| • Stability |

DISADVANTAGES:

- | |
|-------------------------------|
| • Small sampling fraction |
| • Radiation damage (neutrons) |
| • Cost |

LIQUID ARGON (HELIOS, SLD, D0, H1)

ADVANTAGES:

- Long term stability
- Granularity

DISADVANTAGES:

- Hermeticity (cryogenic)
- Slow

WARM LIQUIDS (UA1)

ADVANTAGES:

- Hermeticity

DISADVANTAGES:

- Signal/noise ratio
- Technologically difficult

GAS GAIN CALORIMETERS (LEP experiments)

ADVANTAGES:

- Cost
- Granularity

DISADVANTAGES:

- Very small sampling fraction
- Rate capability
- Alinearity (saturated mode)

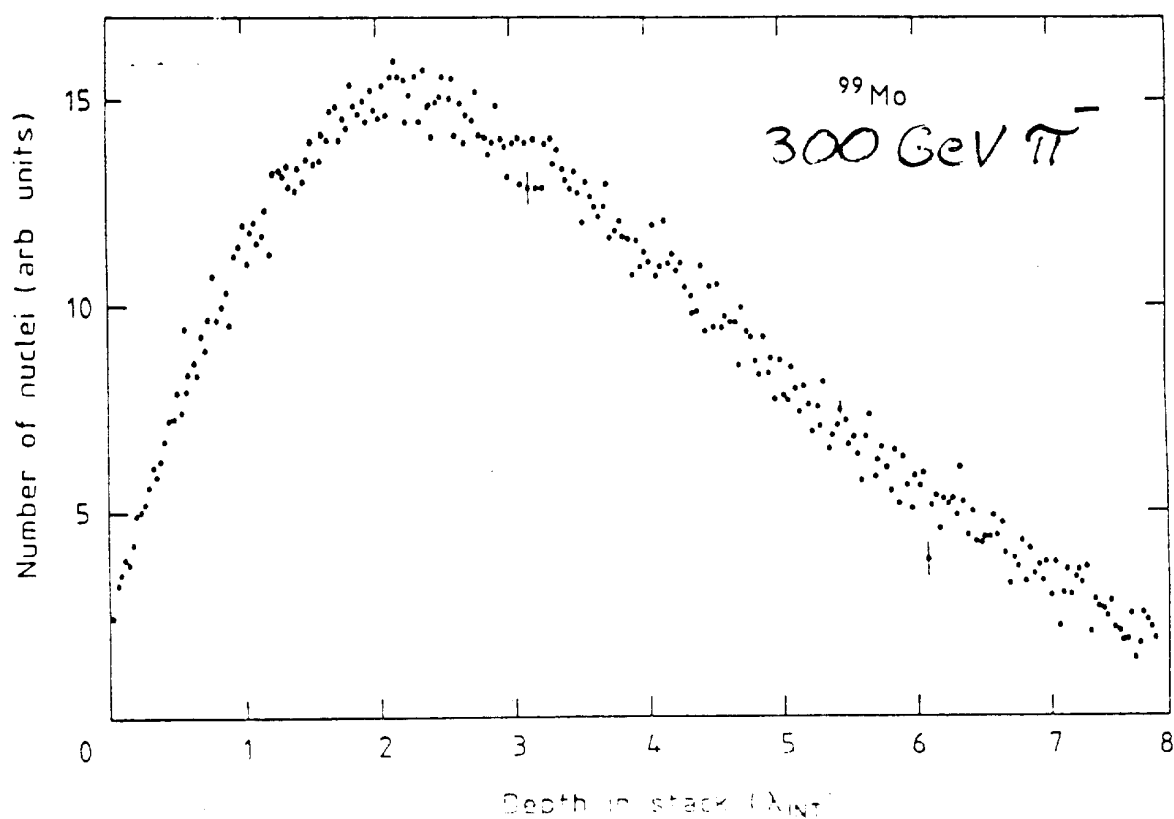
HADRON CALORIMETERS

GENERAL CHARACTERISTICS

- Conceptually, hadronic shower development similar to em, but
- Strong interaction → wide variety of reactions
- Meson production (π , K , but also π^0 , $\eta \rightarrow \text{em!}$)
- Nuclear reactions (p , n , α)
- Energy losses: Binding energy, target recoil, μ , ν
- DIFFERENCES EM/HADR. SHOWERS RELEVANT TO CALORIMETRY:
- Shower dimensions
- Invisible energy
- Non-relativistic shower particles (→ sampling, saturation)
- Neutrons (not subject to em interaction)
- Strong interaction → scaling with nuclear interaction length λ_{int}
- Shower profiles, leakage, $\log(E)$ dependence
- Electron/hadron separation
- $\lambda_{\text{int}}/X_0 \sim Z \rightarrow$ high- Z absorbers
- possible with longitudinal and lateral shower information
- Granularity
- Monte Carlo simulations much less reliable than EGS 4

PROFILES OF HADRONIC SHOWERS

LONGITUDINAL



LATERAL

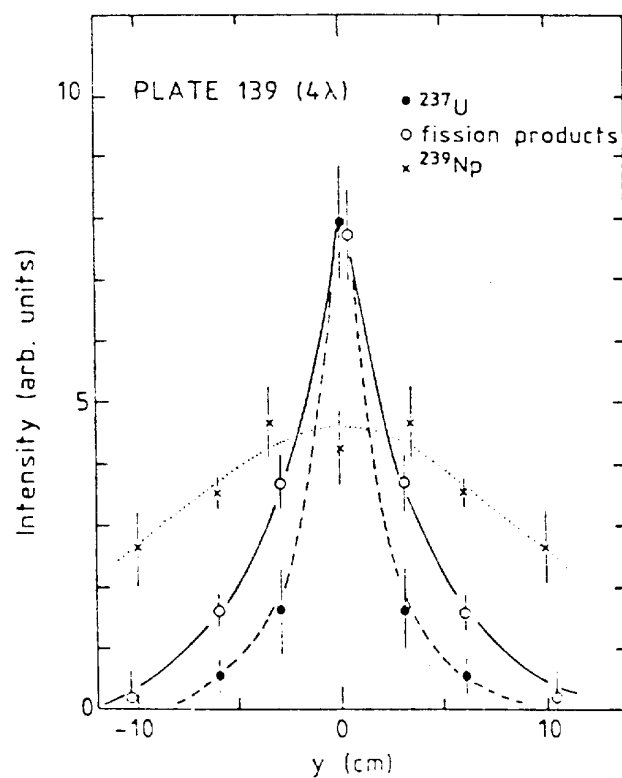


Figure 18

NUCLEAR INTERACTION INDUCED BY 3.8 GeV π^-

Early example of the nuclear interaction of a π^- -meson of energy 3.8 BeV

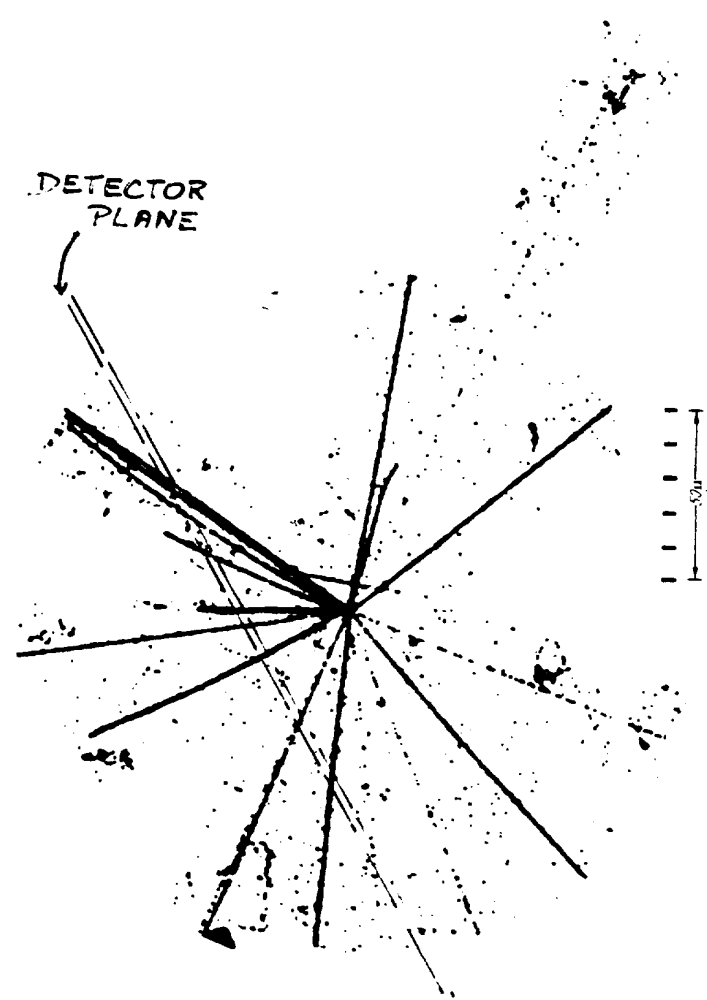


PLATE 11-9

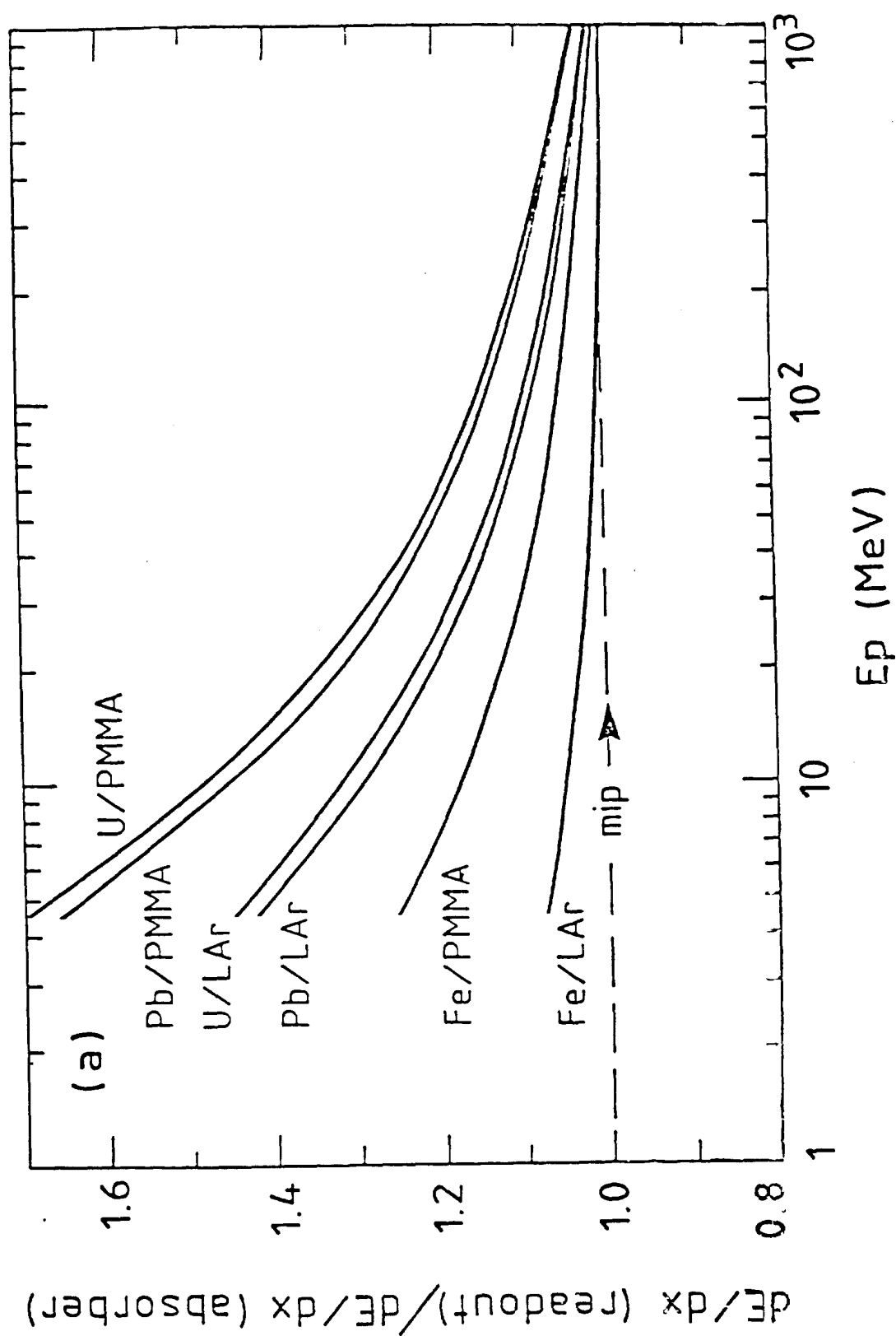
Photo by Thomson

Revised by A. J. G. (1952), unpublished

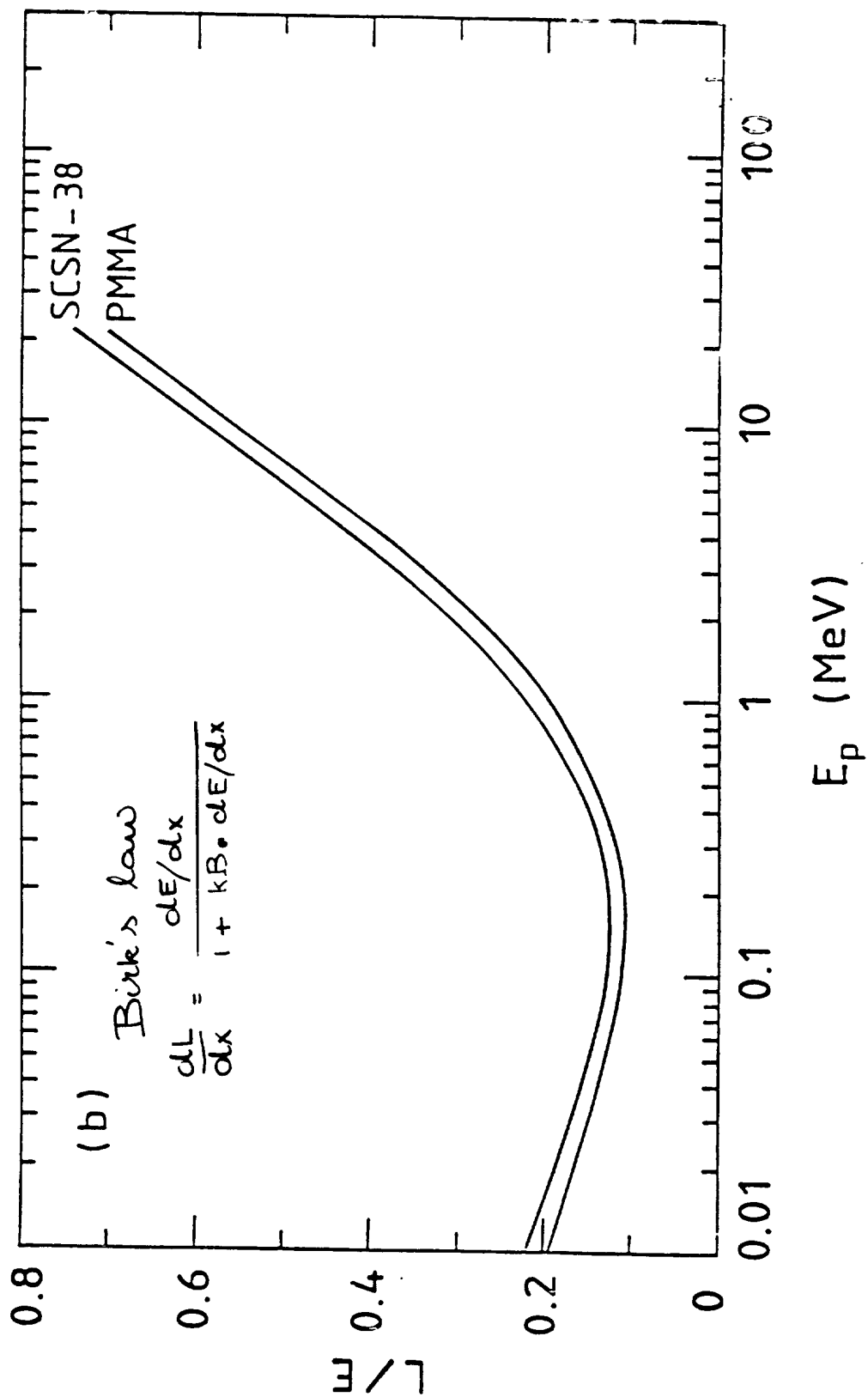
A π^- -meson of energy 3.8 BeV, emitted from a disintegration of type 7-10p, produces a secondary disintegration of type 18-17. It is probable, but not established, that several of the lightly ionizing secondary particles are π^- -mesons.

Figure 30

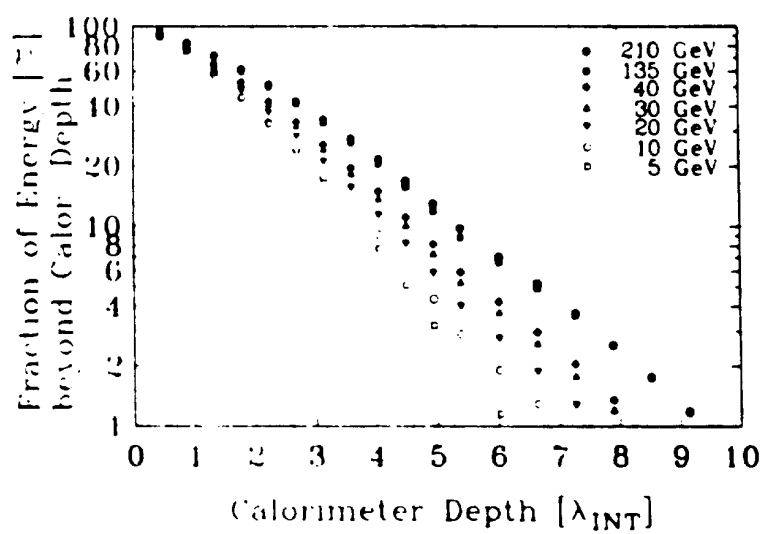
IONIZATION BY NON-RELATIVISTIC PROTONS



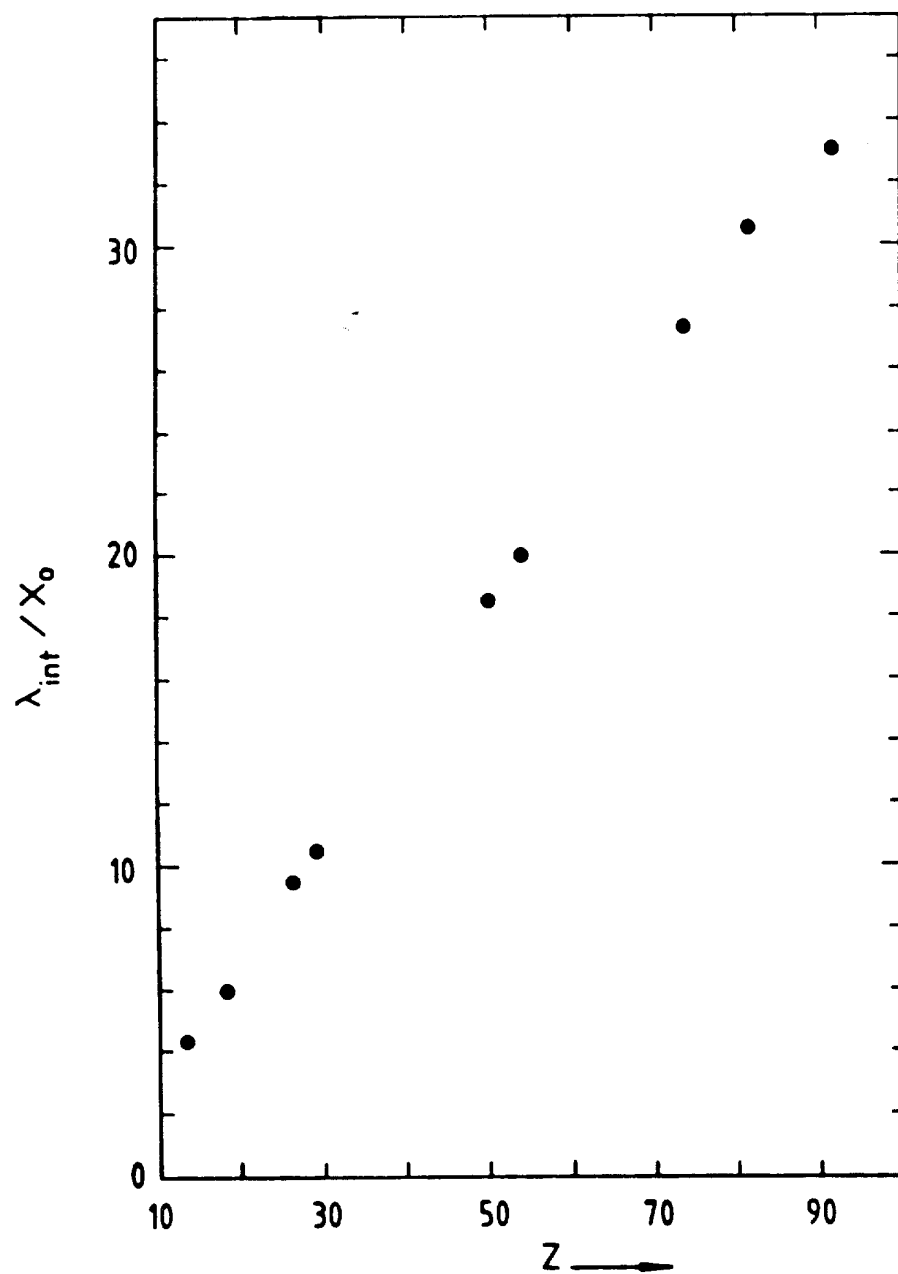
SATURATION OF SCINTILLATOR RESPONSE TO LOW ENERGY PROTONS



HADRONIC SHOWER LEAKAGE



PARTICLE IDENTIFICATION: λ/χ_0



ZEUS

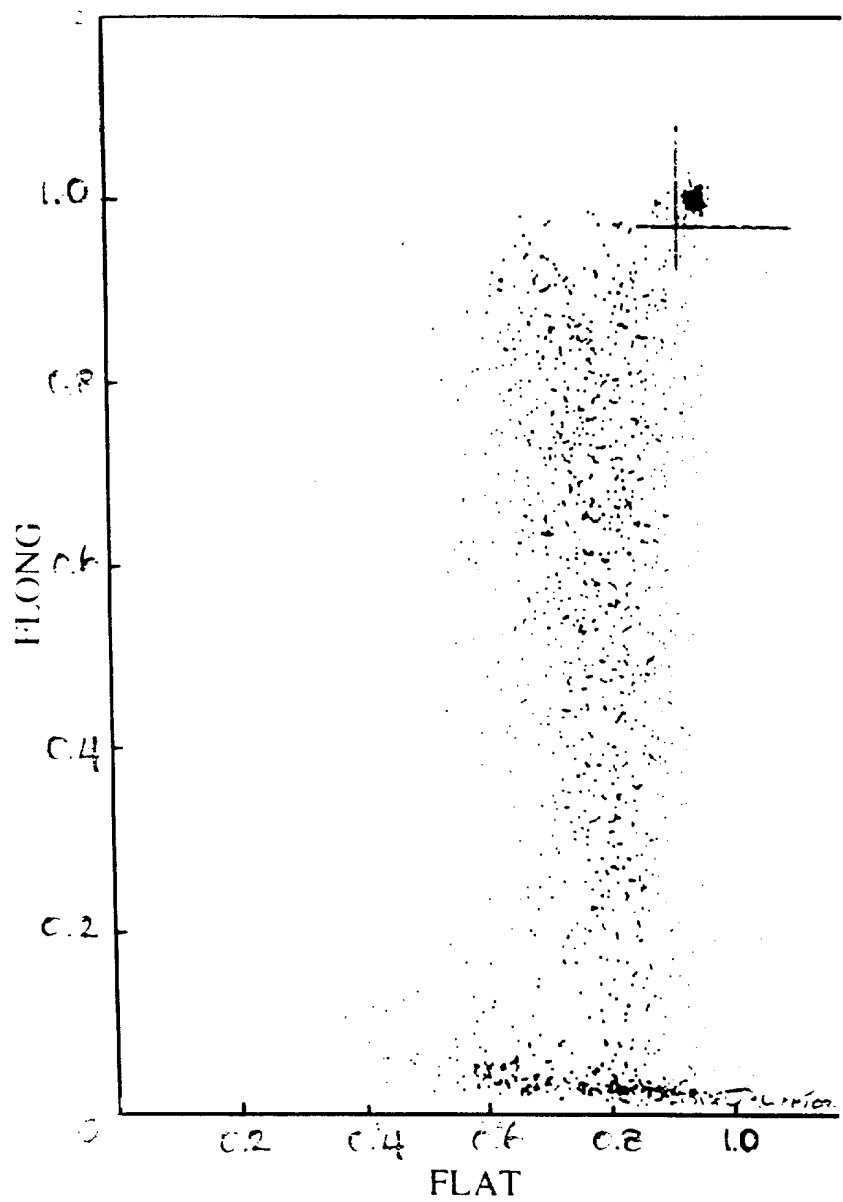


Fig. 3

CONSEQUENCES $e/h \neq 1$

- Signal distribution not Gaussian
- Fluctuations fraction π^0 's $\rightarrow \sigma/E \neq c/\sqrt{E}$
- Signal $\neq E$ (alinenarity, f_{em} function of E)
- Measured e/π signal ratio function of E

Experimentally confirmed

$e/h = 1 \rightarrow$ "Compensating" calorimeter, i.e. equal em and non-em calorimeter response

CONSEQUENCES $e/h \neq 1$ FOR DETECTORS AT SUPERCOLLIDER

- σ/E factor ~ 5 worse
- Trigger biases
- Problems unfolding E_T

How can we make a calorimeter compensating?

(works only for sampling calorimeters)

ENERGY RESOLUTION OF HADRON CALORIMETERS

Energy resolution worse than for em shower detection

- Sampling fluctuations larger than in em showers
- Correlated hits (1 π may ionise 50 active layers)
- Fewer hits for same signal (non-relativistic particles)

- Fluctuations in the fraction of E going into ionizing particles (ΔB)
$$\langle \Delta B \rangle_{\text{non-em}} = 40\% \pm 30\%/\sqrt{E}$$

- Effect of $e/h \neq 1$ (non-compensation)

SIGNAL DECOMPOSITION: HADRONIC SHOWER,
(Predictions for π^0 not Gaussian)

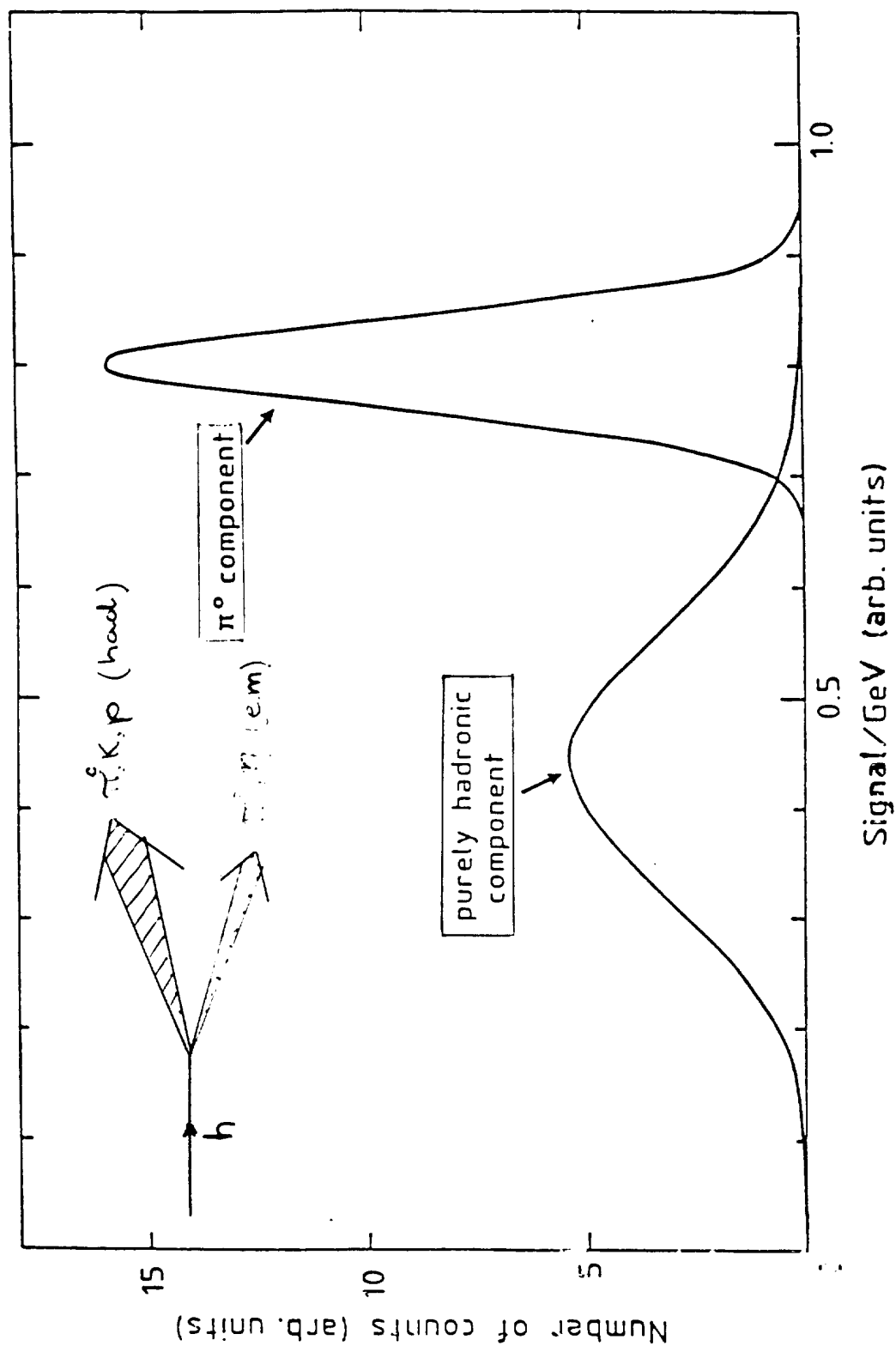
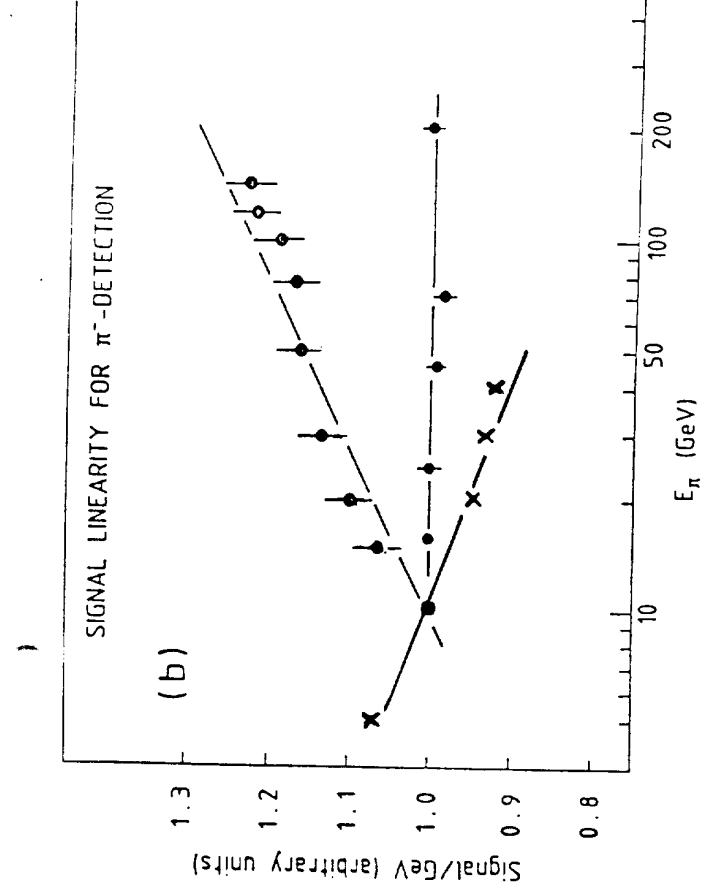
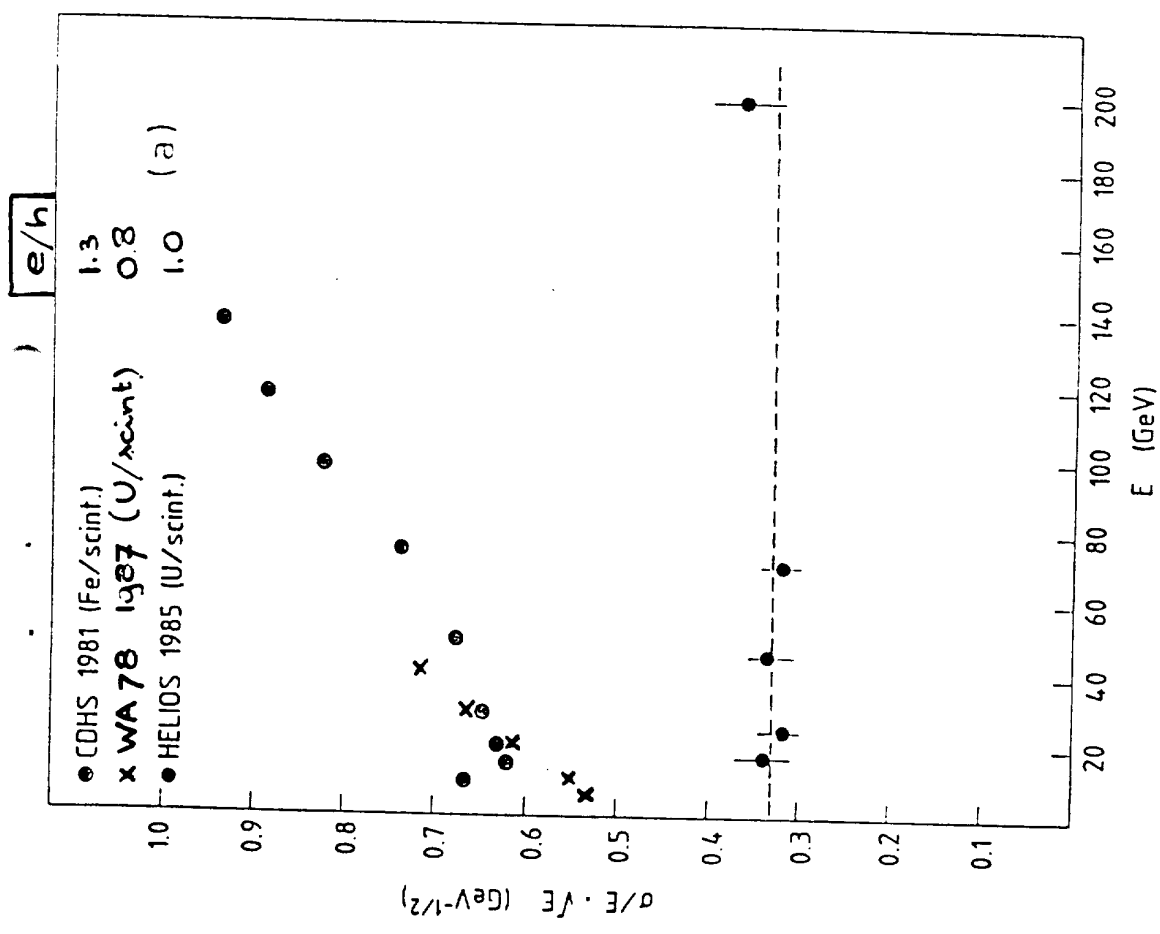


FIGURE 1

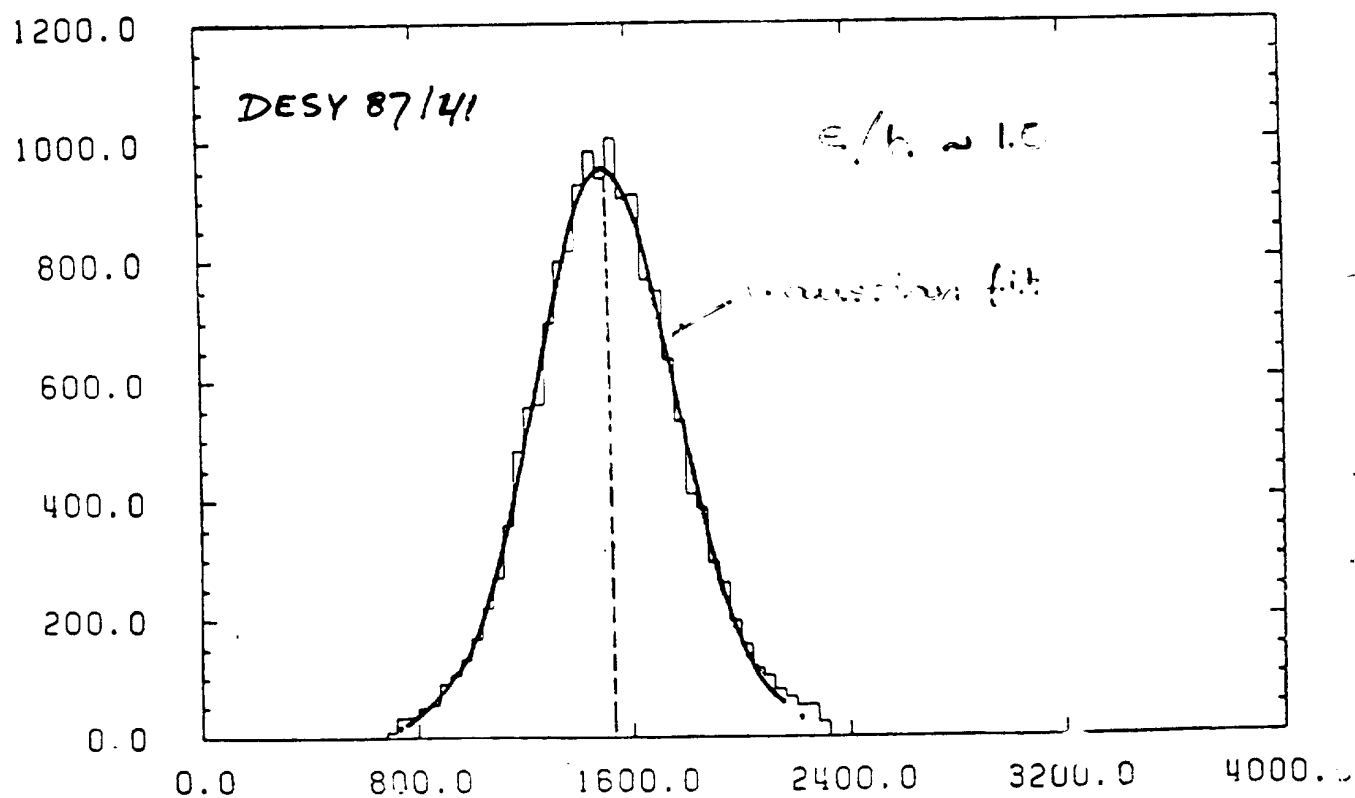
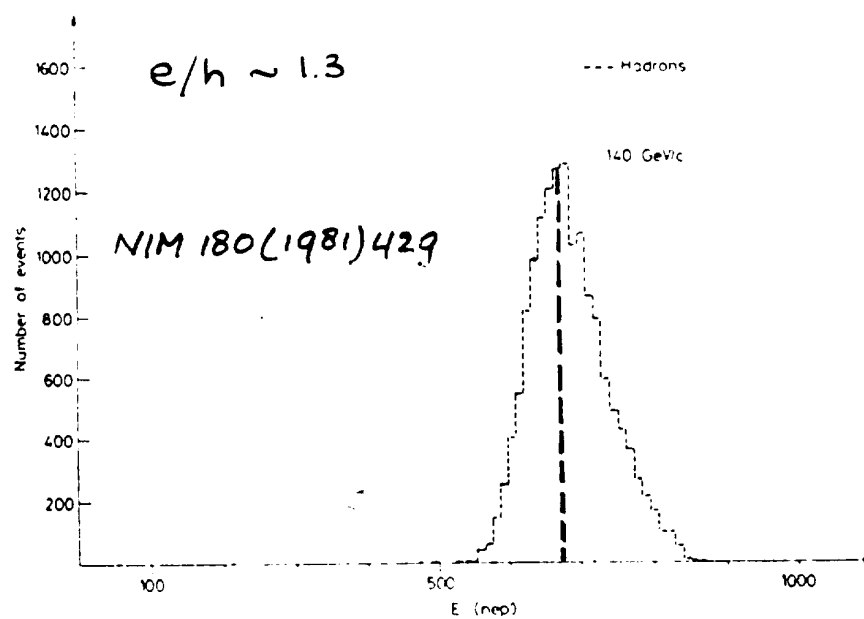


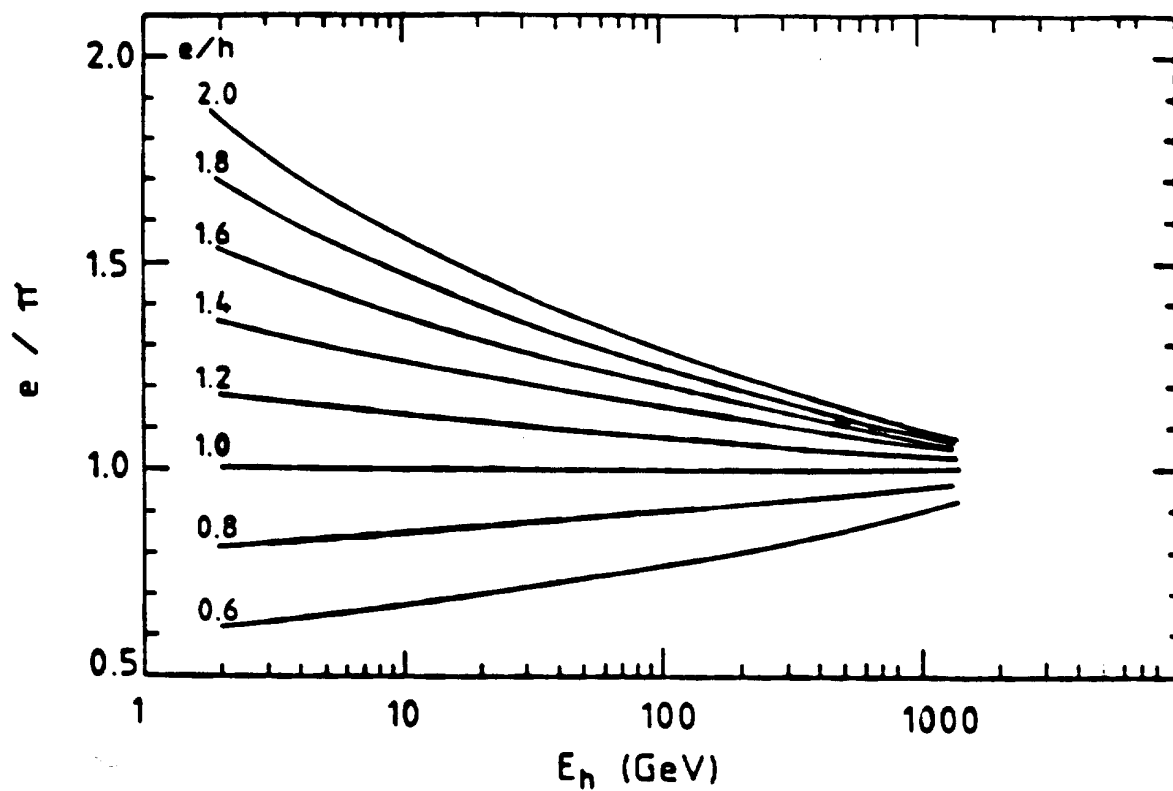
EFFECT OF e/h ON
ENERGY RESOLUTION AND
SIGNAL LINEARITY
(EXT.)

{ NIKHEF 37-02 }
{ NIM 180 (1981) 429 }
{ DESY 87/27 }

Figure 24

HADRONIC LINE SHAPE



RELATION e/h vs e/π 

HOW TO ACHIEVE COMPENSATION?

- Naive expectation: $e/h = 1/0.6 \sim 1.6$
- Lesson from em calorimeters: Calorimeter response decisively determined by details of last stages shower development.

3 MECHANISMS EXPLOITED TO BRING $e/h \rightarrow (\downarrow) 1.0$

- a) Boost h by using ^{238}U absorber plates (nuclear fission). Neither essential nor sufficient
- Relative contribution of the different shower components (π^0 , ionizing hadrons, n , γ) to calorimeter signal can be varied within certain limits \rightarrow e/h can be tuned
- b) Reduce e (π^0 -response) using low- E peculiarities of em shower development (photo-electric effect) \rightarrow high- Z absorber, low- Z active material.
Effect amplified by low- Z passive shielding active layers.
- c) Boost h by amplifying the relative response to neutrons through the sampling fraction
 - 10 – 15% of non-em energy carried by low- E neutrons.
 - Compensation: $\sim 40\%$ of signal comes from low- E neutrons
 - Hydrogenous active material essential
 - Saturation properties crucial